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Development of an expert system as applied to rapid tooling techniques for injection molding

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May 2005

DEVELOPMENT OF AN EXPERT SYSTEM AS APPLIED TO RAPID TOOLING TECHNIQUES FOR INJECTION MOLDING

Andrew T. Haglin

A Thesis

Presented to the Graduate and Research Committee

of

Lehigh University

In Candidacy for the Degree of

Master of Science

in

Mechanical Engineering and Mechanics

Lehigh University
Bethlehem, Pennsylvania

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This Thesis is accepted and approved in partial fulfillment of the requirements for the Master of Science

John P. Coulter, Ph.D.
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April 26, 2005
Date

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ABSTRACT

Rapid tooling has become the accepted way of producing molds for injection molding inexpensively, with better quality, and less cost than a standard production mold. There are approximately 40 techniques that are in various stages of availability. The primary objective of the proposed research study was to identify a means by which to compare these currently available rapid tooling techniques. This study contains an in-depth discussion of each of the currently known rapid tooling techniques, a brief explanation of expert systems, a method of comparing the rapid tooling techniques and, finally, the development of an expert system. This expert system was developed in order to assist in the selection of a rapid tooling technique for any given application. Case studies from various industries were performed to demonstrate the utility and limitations of the resultant expert system.

1 INTRODUCTION

The design and manufacture of new products is time consuming and expensive. A method which can decrease the time spent on producing the prototype tooling and the cost would be widely accepted. This new method is called Rapid Tooling. The use of rapid tooling can cut prototype tooling costs down by 75% and lead time by about half. Right now there are about 45 different rapid tooling techniques that can produce parts ranging in sizes from very small and complex to large and simple. These techniques will be reviewed in further detail later.

1.1 PURPOSE OF THE STUDY

Currently there are approximately 45 techniques for rapid tooling in the market. Among these, there are about five techniques which are still under development at universities all over the world. These developing techniques are trying to get approval from consumers, as well as applications to test their process. They are in the late stages of development but are not yet commercially available. It is the purpose of this study to identify all of the different rapid tooling techniques, either commercially available or under development and compare them using an expert system.

Since there are so many techniques available, a need existed for an effective way of comparing them. With this in mind, an associated expert system was developed. The use of expert systems is growing rapidly in today's society because companies are looking to cut costs by removing people from jobs and replacing them with computers. This expert system asks the user questions' regarding the technical and business attributes of the target manufacturing application and then produces a set of candidate rapid tooling techniques which match the parameters given. The results generated using this expert system should be viewed as recommendations at this point because there is still a large amount of information that remains unknown for some of the techniques. The purpose of this expert system is to get the user started with technique selection. The program provides the user with the techniques matching the chosen parameters and then outlines each of the techniques in further detail. In order for the user to make the right decision, the user will have to do some further research on each of the techniques recommended. Even though the user will still have to do this research on the techniques, there will be a starting point of a few potential rapid tooling techniques to look at, instead of 45 or more.

1.2 OUTLINE OF THE THESIS

This appears to be the first time that a study has been done on producing an expert system for rapid tooling as applied to injection molding. Thus, at the onset of the study a significant amount of background research on both the different rapid tooling techniques and experts systems was required. This thesis will begin in Chapter 2 with the review of all the rapid tooling techniques identified during this process. The techniques will be separated into two different categories, direct and indirect tooling. These two main categories of tooling production are to some extent already accepted by industry. Once the techniques are classified as direct or indirect, they are then separated into soft and hard tooling subcategories. Following this, each technique is described in detail as to how it works, who does the work, and some of the capabilities of the technique.

After completing the review of all the different rapid tooling techniques, a detailed explanation of expert systems is needed. Thus Chapter 3 begins with a background of where expert systems came from and how they evolved. Then a brief description of how expert systems are developed is presented along with and the different types of expert systems that are available. Expert systems are becoming a widely used method of troubleshooting and new applications are being found everyday. Applying an expert system to rapid tooling is one of the more obvious beneficial applications; however, every new application found helps prove the validity of expert systems.

With the background information completed, the actual development of the expert system for rapid tooling can begin. In Chapter 4, the development of this expert system begins with the identification of the proper software needed and the proper representation of knowledge going into the program. Selecting the right software is vital because if the wrong software is used, it could become very difficult to achieve the desired results. Upon finding the right software and deciding on a representation method, the program needs to be written and tested. The actual process of programming is then laid out in detail and explained as to why certain techniques were utilized.

Writing a program is the easiest part of the process because it is just a matter of ensuring that the syntax is correct and the information is entered. The hardest part of developing any program is the testing and debugging. In order to due this efficiently, case studies were identified. These case studies were real world applications taken from the automotive and aerospace industry, the electronics industry, schools and the toy industry. These case studies, presented in Chapter 5, serve as useful tools in identifying the capabilities and limitations of the program.

Lastly, once the case studies have been run through the system, the results and the problems that were encountered will be discussed in Chapter 6. The problems encountered will be corrected and the program rerun to ensure that the problem was eliminated. Once all the problems have been eliminated there is a final discussion of the research in Chapter 7.

1.3 TARGET PROBLEM DESCRIPTION

The cost of prototype tooling and required lead time to develop it are both extremely high. For a company to bring a new product to the market, the prototyping stage will cost them at least $20,000 dollars and approximately two months per prototype mold needed, on average. These numbers are used to keep researchers from needing to make corrections to the molds, which probably adds more time to the production schedule. Many companies are constantly looking to save money in this prototyping stage. The answer to this problem is rapid tooling. Before rapid tooling, companies were rushing products to the market to save money and in the end they were spending more because new models of the same thing would come out and replace the older models. This process of model replacement can be done away with by using rapid tooling effectively.

Rapid tooling allows a company to produce a prototype mold for about $5000 dollars and the lead time can be four weeks or less, depending on the product. This reduction in cost and time allows companies to make more changes to ensure that the product hitting the market is right. The problem with rapid tooling is not that it is effective and cost efficient, but there are just too many techniques and the number of options is growing every year. Currently there are approximately 45 different techniques out there and each is at a different stage of technical availability. The other problem with these techniques is that they are designed with different product sizes and complexity levels in mind. Some techniques are good for certain materials, while others are concerned with the surface roughness and tolerances. Rapid tooling is so diverse that there needs to be a way to effectively differentiate between all of the different techniques and to determine the right technique for every application.

1.4 THE SOLUTION

To solve this problem of having too many rapid tooling techniques, an expert system was developed. This expert system helps determine the proper rapid tooling technique for every application by using an elimination process. When a company has a part that needs to be made and wants to save money, the expert system can be run. The user is asked a list of questions and answers each of them by selecting a particular value. The program then searches through the entire database of techniques and attempts to match the desired parameters with rapid tooling techniques. The program then outputs the results to the main console and asks the user for further information. If the user so decides, the program then outputs each of the resultant techniques and lists its detailed capabilities. The program thus serves as a recommendation tool or starting point to help the user identify the proper rapid tooling process for their application.

Expert systems as applied in cases like this do things that humans can do. In most situations, however, they are more accurate and more consistent than humans. Expert systems will not miss matches and render decision making systems less susceptible to human error. The use of expert systems in this case will allow for a more reliable resource in finding the right techniques.

2 BACKGROUND OF RAPID TOOLING

In today's world there is an ever-changing need for new technology and new products. In manufacturing, this means faster product development and reduced time-to-market. Most importantly, with faster product development, there needs to be a reduction in product cost. Meanwhile, the consumers are demanding an increase in product quality. Over the past two decades, there have been significant advances in the field of manufacturing, in an effort to decrease time-to-market, while maintaining a high quality and technically advanced product. One of the first steps in this direction was the incorporation of rapid prototyping (RP), which allowed the design team to determine some of the product characteristics before time and money is spent on molds for actual part production. Figure 2-1 illustrates the flow of data starting with the 3D CAD file and ending with the physical part model.

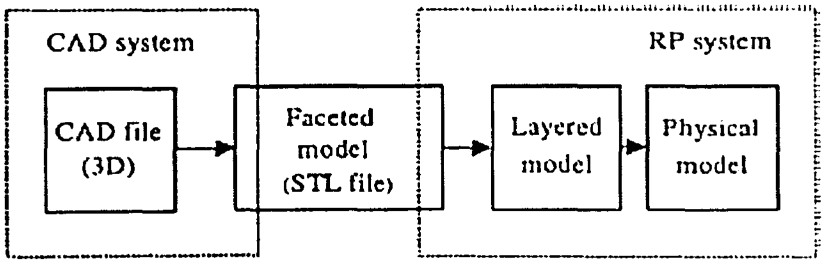


Figure 2-1: Data transfer between the CAD and RP system [1, 2]

The RP process helps engineers visualize design defects and identify assembly problems, while attempting to gain market acceptance. Most often, a material is selected for the RP process based on its mechanical and physical properties. The chosen material often mirrors, but is not the same as the intended production material.

"Rapid tooling is not a new idea; it has simply co-existed with conventional machining for many years." [3] The idea was first revisited in the 1990's as a potential solution to the need for more parts in a shorter time, and it has also been proven useful in making key production planning decisions early in the development process. In order to be an ideal RT process produced tool, it must demonstrate all of the following attributes, namely:

- Little or no required additional rework on the finished tool;
- A sufficiently hard tool surface;
- No limits to tool size or part geometry;
- High production runs;
- Reduced tooling time; and
- Production of tools capable of molding the intended material.

What does this mean for rapid tooling? Rapid tooling techniques reduce time to market and increase the competitive edge [4]. For example, RT techniques can produce anywhere from 10 to 5000 parts for design testing, function testing, and molding problem identification. These parts are also used as marketing tools, testing the consumer's impression of the product. Also, RT can be used for short production runs in order to avoid the often high costs associated with production tooling.

2.1 CLASSIFICATION OF RT PROCESSES

As advances in this field are made, the production of tools will remain difficult due to strict requirements placed on them. The molds must withstand high injection and holding pressures, possess wear resistance to ensure long lifetime, and have good surface finish to avoid additional tooling/finishing operations, thereby permitting easy ejection from the mold.

Since the RT field is growing rapidly, it has become necessary to divide the techniques into classifications to help differentiate between each process. The two main classifications are indirect and direct rapid tooling, as shown in Figure 2-2.

Even though specialized RP processes can produce a good tool, in many cases there is still a need for an actual model of the product to be built first from a standard RP process. These techniques are classified as indirect tooling techniques because they include at least one intermediate step in the tooling process. The part made by the RP process is used as a pattern for the tool.

On the other hand, direct RT processes are simply specialized forms of current rapid prototyping processes. These RP processes, such as "Direct Metal Laser Sintering" (DMLS), and "Laminated Object Manufacturing" (LOM), have been adapted for the specific application and material desired. As is common to both techniques, there are plenty of related processes that are commercially used today, while others are still under development.

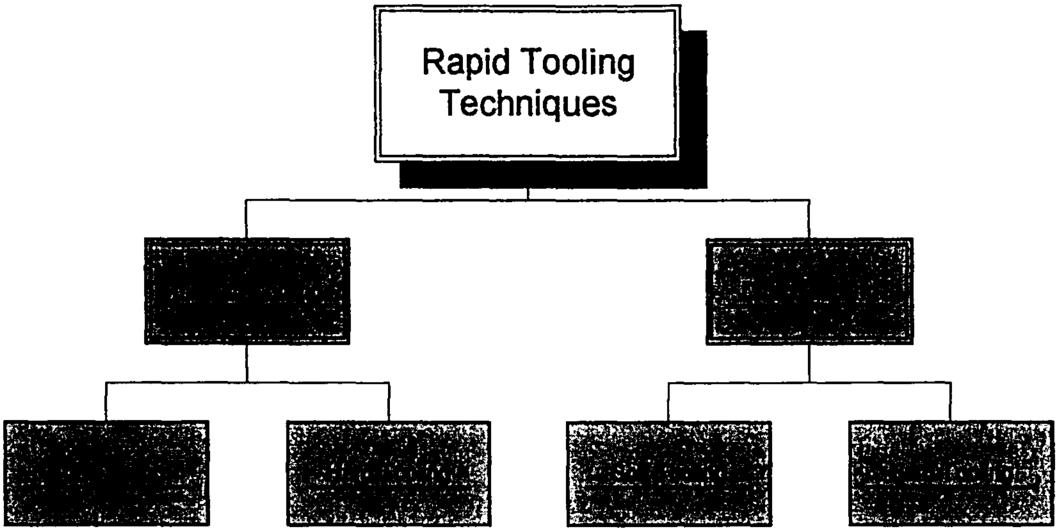
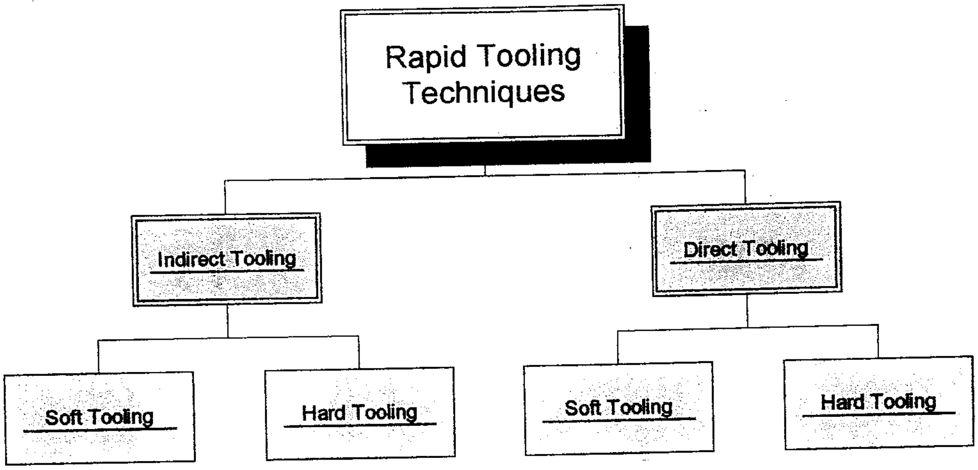


Figure 2-2: Classification Chart of Rapid Tooling Classifications

To help with the understanding of RT, direct and indirect methods can be further divided into two subgroups, namely soft tooling and hard tooling (Figure 2-2), although, the difference between the two can often be confused. Hard tooling is defined as tooling that is made of metal, which is used for high production quantities, whereas soft tooling is mainly made typically using polymers or other non-metallic materials, which are intended for small to medium production quantities.

2.2 INDIRECT RAPID TOOLING PROCESSES

Most RT techniques today are 'indirect', meaning that a preliminary RP of the product is used as a pattern for making the mold. Indirect processes were the first techniques used for rapid tooling because they use the parts made with the RP processes. The need for tools to produce short production runs required moderately strong, low cost tools, which couldn't be accomplished by machines of the past. Thus, the field of indirect rapid tooling came into play. While different applications of rapid



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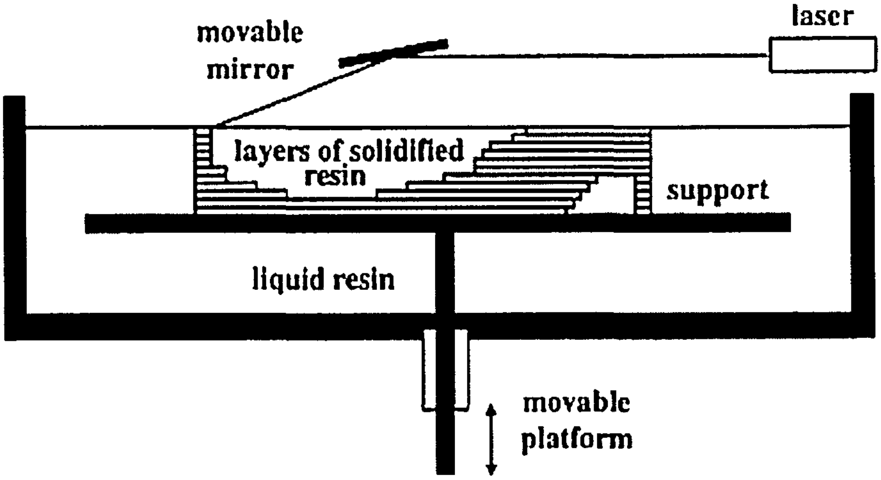

Figure 2-3: Principle of SLA [2]

Furthermore, in order to help with the understanding and to make the classification easier, the indirect tooling techniques were subdivided further, into two sub-categories, namely, 'indirect soft tooling' and 'indirect hard tooling'. Figure 2-4 illustrates the classification of all the indirect soft tooling techniques that are either commercially available or under development.

2.2.1 Indirect Rapid Soft Tooling Techniques

As stated previously, indirect tooling processes utilize RP fabricated patterns to produce tools. The first classification of indirect tooling is soft tooling. There are two types of indirect soft tooling that are commercially available. These are RTV silicone rubber molds, and aluminum-filled epoxy tooling.

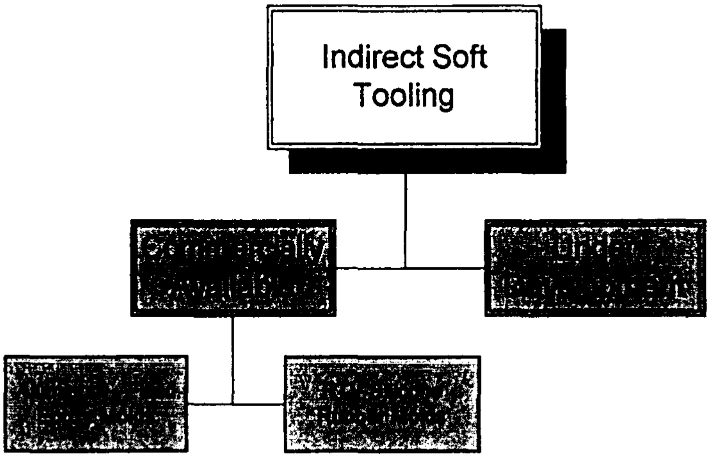

Figure 2-4: Classification Chart of the Indirect Soft Tooling Techniques

2.2.1.1 RTV Silicone Rubber Molds

This process is the most widely used due to its easy, inexpensive, and fast fabrication capability. The main disadvantage to the RTV process is the inability to produce prototypes in materials other than vacuum-cast polyurethane. Due to the flexible nature of rubber these molds cannot be used for injection molding, and also because of the molding material, the mold requires one full day to cure before the RP pattern can be cut free from the rubber mold. This process, however, is the foundation of a large number of other techniques to be described later.

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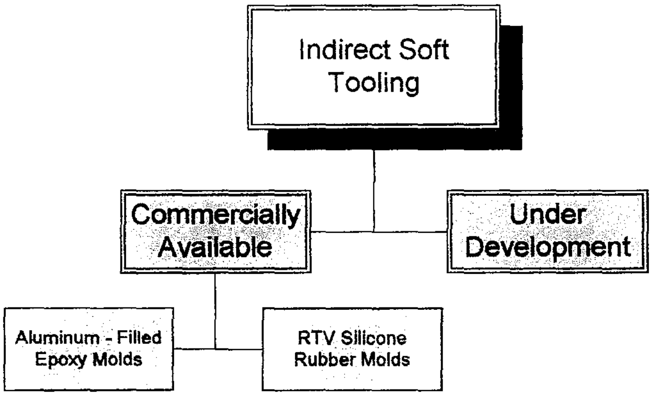

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The RTV process begins with placing the RP pattern into a mold box. Next, the RP pattern is embedded in plasticine to the desired height providing a parting line for the finished tool. A release agent is then sprayed on the exposed half of the pattern and silicone rubber is poured, forming one half of the mold. Once the rubber is cured, the half-mold is flipped over allowing for the venting and gating to be cut into the cured rubber at the desired locations. Finally, silicone is poured onto the second half, completing the tool. It is to be noted that the silicone is typically a tin and platinum based rubber to provide strength.

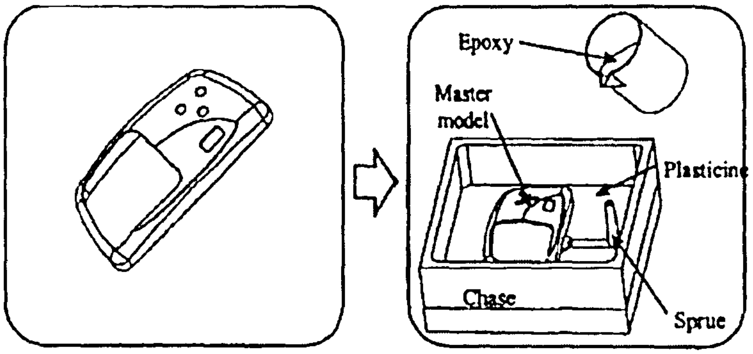
The RTV process is best suited for simple geometries with no sharp edges or thin walls. Also, it can produce approximately 50 parts per mold at relatively low temperatures and low pressures before showing signs of wear. Refer to Appendices A and B for a more in-depth look at the technical and business attributes of the RTV process. If all that is desired is to produce market-testing samples for aesthetic testing in a material similar to the intended material, then this process will work. For testing a specific material and complex shape, this process will not be effective. [5]

2.2.1.2 Aluminum Filled Epoxy Tooling

The use of epoxy-filled molds is the fastest way for producing short runs of functional parts by injection molding. The process is much like RTV, where the RP pattern of the product and the sprue and runners are embedded in plasticine up to the parting line. The exposed half is sprayed with a releasing agent and then the aluminum filled epoxy is poured over the pattern forming the first half of the tool.

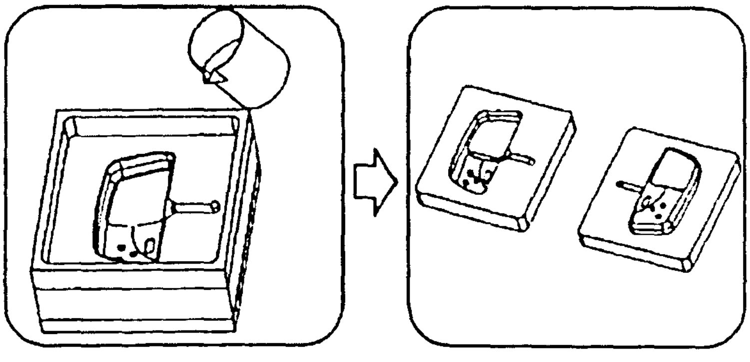
This procedure is repeated on the other side forming the second half of the mold. Finally, the RP master is removed from the finished tool. Figure 2-5 shows the schematic description of the process.

The addition of aluminum fibers strengthens the epoxy resin, while supplying the cavity with high wear resistance and increased thermal properties. There is some machining required at process completion, but this machining is to help fit the two tool halves together, after which the tool is ready to be put into the injection-molding machine.



Master Mold

Embedding of the model in plasticine along its parting line and backfilling with epoxy



Inversion of the first half of the mold and backfilling

Epoxy injection molding inserts

Figure 2-5: Illustration of Aluminum-Filled Epoxy Tooling [6]

Due to the material used, the tools cannot be subjected to extremely high pressures or they will break down. These tools, depending on the geometry of the part, can produce over 500 parts per mold with little to no signs of wear on the tool surface. Even with the addition of the aluminum fibers to the epoxy resin, the cycle times are still slightly higher than those with conventional metal tools. This is because of the low thermal properties of the epoxy resin. Aluminum filled epoxy tools are typically designed as inserts. Refer to Appendices A and B for a more in-depth look at the technical and business attributes of this process. [2, 6]

2.2.2 Indirect Rapid Hard Tooling Techniques

Indirect hard tooling techniques are those in which RP patterns of the desired product shapes are typically used to make longer lasting metal tools. There are a large number of indirect hard tooling techniques that are commercially available and under-development, more so than any other type. Figure 2-6 illustrates the classification of the indirect hard tooling techniques that are either commercially available or under-development.

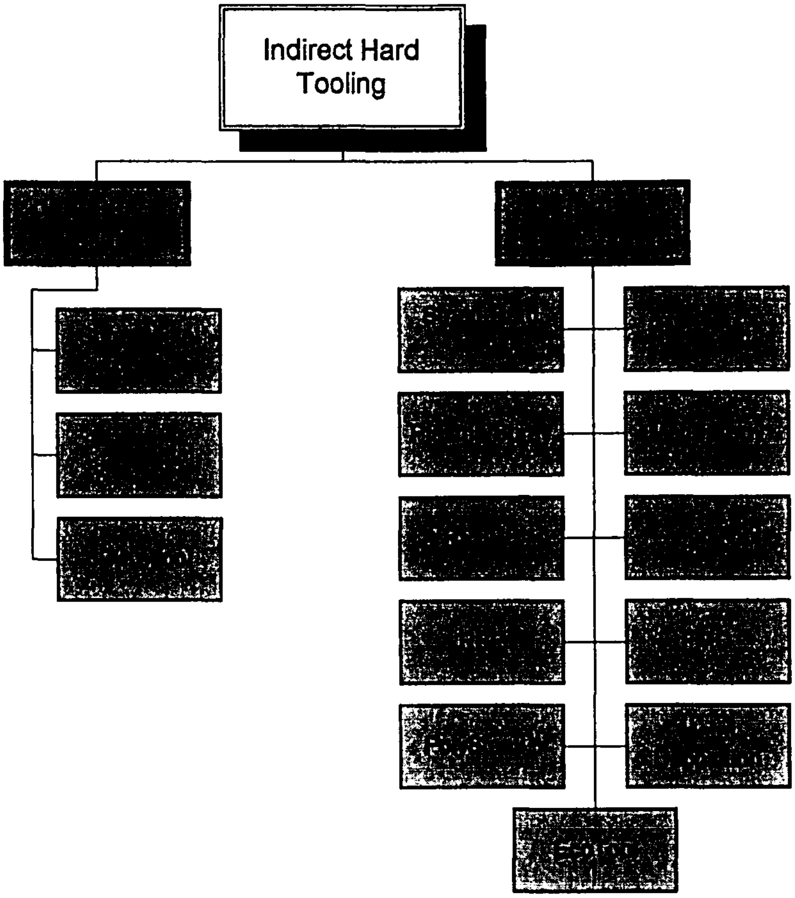


Figure 2-6: Classification Chart of the Indirect Hard Tooling Techniques

2.2.2.1 Spray Metal Tooling

Spray metal tooling (SMT) is similar in nature to the aluminum-filled epoxy tooling. This new process, however, had to overcome two major problems. First, the preliminary RP of the product needs to withstand very high temperatures from the liquid spray. Second, internal stresses are a huge problem in SMT causing deformations in the mold. Once these problems were solved the spray metal tooling process could be implemented.

The process consists of two spools of metal wire fed through a spray gun. At the tip of the gun an electric arc melts the wire and a high-velocity air stream carries the molten droplets to the pattern surface. As the droplets travel from the gun to the pattern surface they begin cooling, so that upon reaching the surface a mechanically bonded coating is formed.

Low-pressure tools for vacuum forming and blow molding are ideal applications for this process. Unfortunately, SMT is a line of sight process, meaning that the spray can only adhere to the visible surfaces. Along with this problem there are other limitations. Of those limitations, complexity of the shape is the most severe. Because this is a line of sight process, the part must be relatively simple. These molds cannot have holes, thin slots, or deep caverns since the spray will have difficulty reaching these types of surface areas causing the mold to have an incomplete surface coating.

The use of a low melting point material produces excellent and accurate tools from the preliminary RP pattern. This technique is great when used on small and large parts alike, but more so with the larger parts. The process becomes much more complex when high melting point materials are considered. Refer to Appendices A and B for a more in-depth look at the technical and business attributes of this process. Figure 2-7 illustrates the spray gun arrangement used for spray metal tooling. [1, 5]

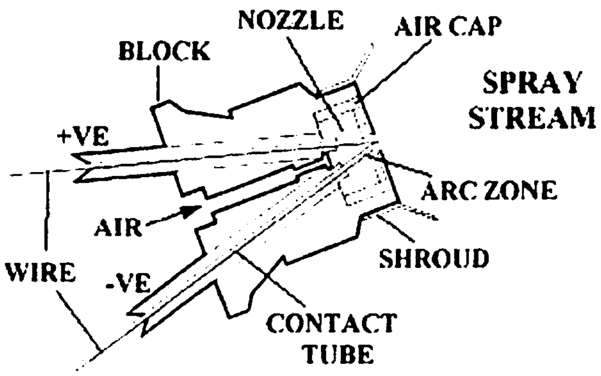


Figure 2-7: Illustration of Spray Metal Tooling (www.metal-spray.co.nz)

2.2.2.2 Cast Metal Tools

Cast metal tools (CMT) can be broken into two different types, namely, sand casting and rubber-plaster casting. Sand casting is used for producing larger tools in aluminum or cast iron, whereas the rubber-plaster casting is used for producing net shape tools. Cast metal tools also have two different techniques to form high strength tools, such as 'spin casting' and 'investment casting'.

Sand casting starts with a preliminary RP of the desired product shape. The sand is packed around the RP producing a sand mold. Then the sand mold is backed with a metallic material to provide strength to the tool. The advantage of sand casting is that it is a cost effective option for the production of large metal tools where surface finish is not a requirement.

Rubber-plaster tooling, on the other hand, produces a near net shape mold, which requires only a minimal amount of finish machining. This process takes a silicone copy of the required tool and applies a gypsum material cast to the copy. Then the silicone is removed, a metallic material is placed where the silicone was and the tool is produced.

An advantage to this process is that conformal cooling channels can be inserted into the molds very easily, if desired. Another good feature to this process is that tool repairs are very easy due to the simplicity of the tool. The difficulty holding tight tolerances and the significant amount of required polishing are just a few of the disadvantages of CMT.

Within CMT, there are two techniques that are used for high strength casting. As mentioned earlier, they are investment casting and spin casting. Investment casting is a good technique for the production of molds with complex shapes and high surface accuracy. Wax patterns are used because of their ability to replicate the pattern with high accuracy. Once the mold has been completed the wax will be melted away and the tool will be ready for molding.

Spin casting on the other hand is slightly more difficult. The process begins with the molding of the RP using the RTV process. Because of the materials used in the casting process, a heat vulcanized silicone material is used for the mold because of its ability to withstand high temperatures. To obtain this silicone mold, first the RTV mold is used to cast a tin based metal alloy mold. This tin based mold is then used to fabricate the heat vulcanized silicone mold. Then the parts can be spin cast. This means that the material is poured into the mold while the mold is being spun at very high speeds. The physical strength of these parts can be compared to that of die cast aluminum parts. Refer to Appendices A and B for a more in-depth look at the technical and business attributes of cast metal tools. [3, 6]

2.2.2.3 3D Keltool™

The 3D Keltool™ process was developed over 25 years ago by 3M. Because rapid prototyping technology didn't exist at the time, the process was temporarily neglected. "3D Systems" has since taken over ownership of the process and has worked on it extensively. This process converts a preliminary RP of the product into a production tool with good surface finish and tool lifetime. This process is so accurate, that the smallest reproducible surface of an RP part is 0.04 mm.

The 3D Keltool™ process uses a preliminary RP pattern of the desired part shape in order to create a silicone rubber mold using the RTV process previously described. The mold is removed and used to cast a mixture of powdered steel, tungsten carbide and polymer binder, which cures to form a so-called "green" tool. Finally, the part is placed in a furnace where the binder is eliminated as the other materials are sintered together. The resulting part ends up being approximately 70% steel with a void level of 30%. The mold is then infiltrated with copper to fill the voids left after sintering. This infiltration completes the mold making it fully dense and increasing its strength.

The 3D Keltool^{TM} process has a lead-time of one to six weeks and costs between $2000 and $5000. Combining good accuracy, an excellent surface finish, and the ability to make multiple inserts from one master pattern, makes this process very effective and popular for parts under 100 cm. However, the biggest problem with 3D Keltool^{TM} is its inability to hold tight tolerances in large molds. Limitations also exist related to the sintering process. Refer to Appendices A and B for a more in-depth look at the technical and business attributes of 3D Keltool^{TM}. [6, 8]

2.2.2.4 Plasma Spray Metal Tooling

Plasma spray metal tooling is currently under development at Tsinghua University in Beijing China. This process is an attempt at adapting the spray metal tooling technique using a high melting point material. The use of higher melting point materials requires the use of a new material, such as ceramic. The mold starts as a CAD file similar to all the other processes. The RP part and a silicone mold are made using the RTV silicone mold method. Next, a ceramic mold is fabricated using the silicone mold as the base. The metal layer is then sprayed onto the surface of the ceramic where the part will be made. Once the metal is cooled, it receives a backing material. The next step is to make the female mold half in the same manner as the male mold half. Finally, to complete the mold, the two mold halves are put together. The powder slurry consists of a ceramic metal composite containing the appropriate amount of metal powder. [9] Due to the high speed of the particles, the ceramic mold needs to possess high tensile strength, hardness rating, heat resistance, and also be easily removable from the RP substrate. The substrate is made in a few quick steps. First, the RP part is sprayed with a lubricant so that it can be removed once the substrate is completed. Then the metal slurry is sprayed over the pattern where it will shrink and solidify, forming the surface. Next, the binders and an interface layer are sprayed onto the hardened metal slurry. Once the binders have cured, the additional supporting material is added. Finally, the mold is heat-treated to remove moisture and any remaining unwanted materials, after which the substrate is formed and is ready for spraying. The stainless steel powder is then sprayed onto the substrate using a plasma-spraying machine. Figure 2-8 illustrates the spray gun arrangement used for plasma spraying.

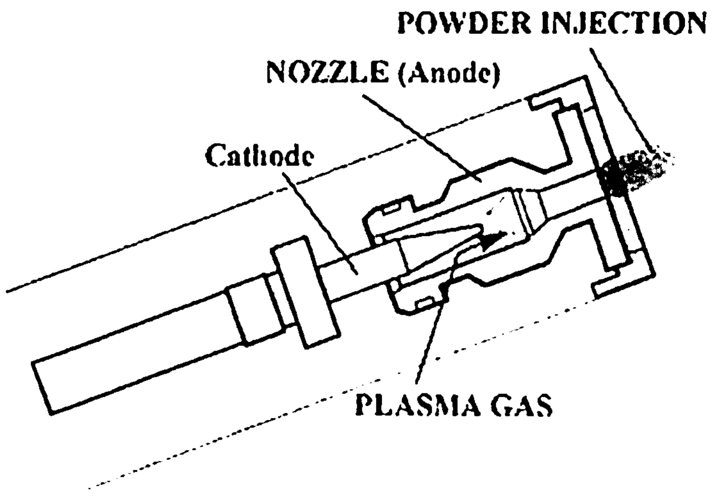
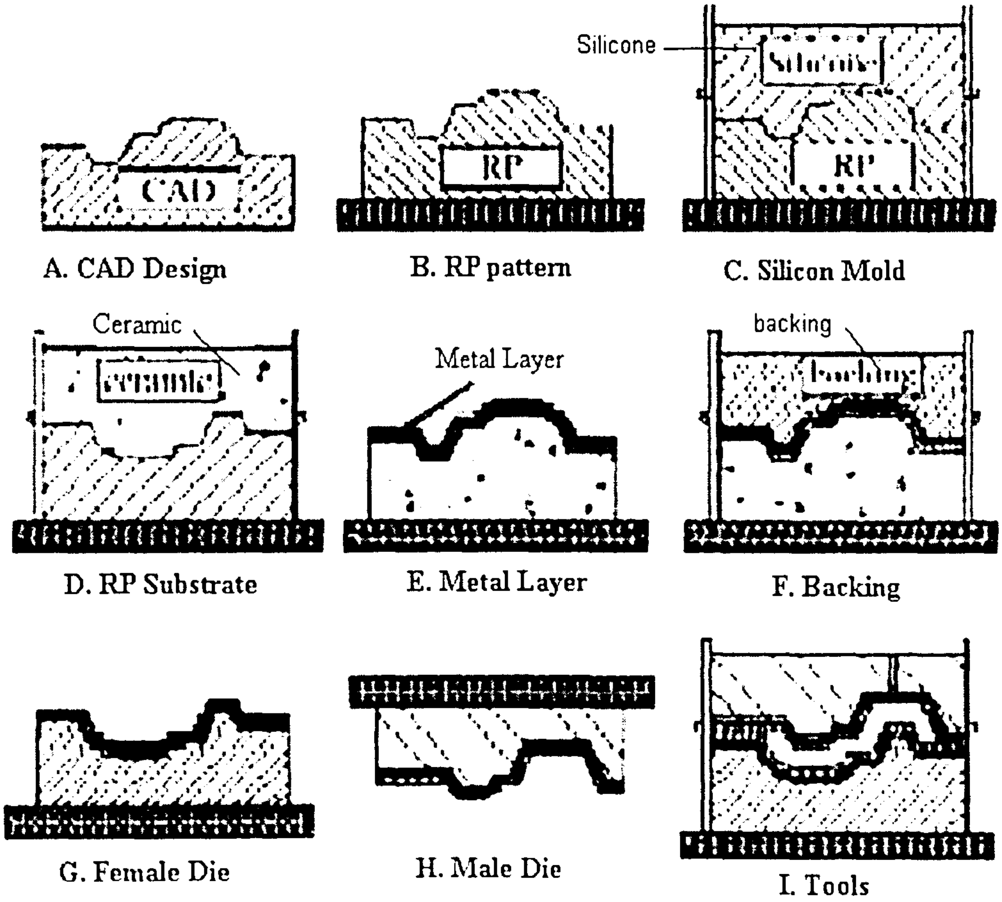


Figure 2-8: Illustration of Plasma Spray (http://www.metal-spray.co.nz)

This process, while certainly time-consuming with a lead-time of approximately six days, is faster than most of the other RT techniques used today.

Another factor that makes this process so appealing is that the total cost of this process runs about $250 per tool. These tools are mainly used for injection molding, but can also be used for sheet forming. The main advantage of this process is the ability to make large tools easily. Although this technique enables the production of large tools easily with a short lead-time, the tools produced, however, have high internal stresses, lack strength and develop cracks relatively quickly. Figure 2-9 briefly illustrates the plasma spray metal tooling process. Refer to Appendices A and B for a more in-depth look at the technical and business attributes of plasma spray metal tooling. [9-11]



A. CAD Design
B. RP pattern
C. Silicon Mold
D. RP Substrate
E. Metal Layer
F. Backing
G. Female Die
H. Male Die
I. Tools

Figure 2-9: Spray Metal Tooling Diagram [11]

2.2.2.5 Rapid Pattern Based Powder Sintering (RPBPS)

Dr. Jack Zhou, a Professor at Drexel University in Philadelphia, PA., developed the Rapid Pattern Based Powder Sintering (RPBPS) technique. This process integrates rapid prototyping with powder sintering. The RPBPS technique offers a variety of benefits including the ability to use metals, ceramics, composites and plastics. The lead-time of this process is approximately one week, including complex molds with a high degree of accuracy and precision. The ability to produce molds with complex geometries in a short amount of time sets RPBPS apart from 3D Keltool^{TM}. The hardness of the tool depends on the material. For example, the process produces a tool with a hardness of HRC 30 – 50 for a metal tool or tool steel powder. The hardness for a tool made of ceramics or alumina powder yields a hardness of HRC 40 – 70. Along with the hardness of the tools, there is a large tensile strength of between 50,000 and 75,000 psi, again, depending on the material used. It is being claimed that tools made with RPBPS will cost approximately one-tenth the price of a standard production tooling. Refer to Appendices A and B for a more in-depth look at the technical and business attributes of RPBPS.

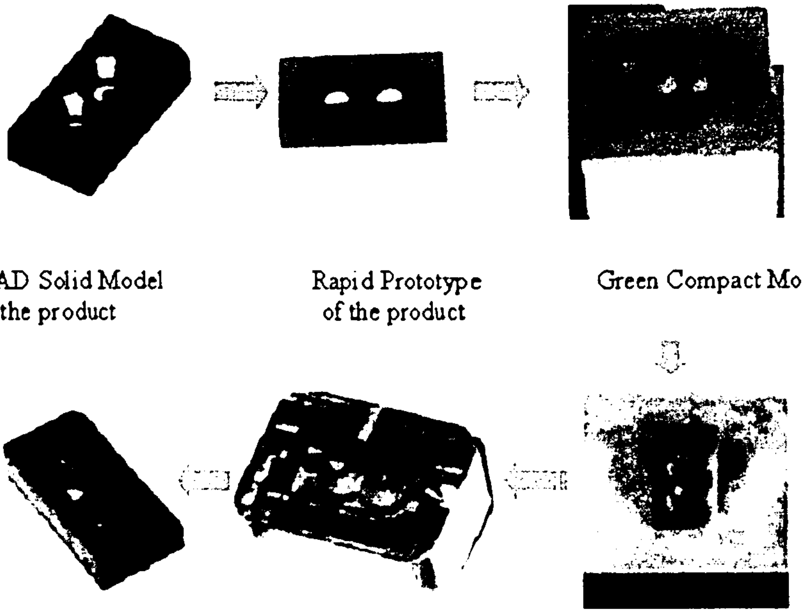


Figure 2-10: Diagram of RPBPS Process [12]

Rapid pattern based powder sintering is similar to 3D Keltool™. First, the CAD file of the intended molded product is used to form a thermoplastic pattern using a RP system. This pattern is then used to make a "green" tool half, which consists of material powders and special binders. This "green" tool half is sintered and infiltrated with copper in a protected atmosphere to increase the final strength and reduce surface roughness of the tool. In comparison to Keltool™, this process produces molds from a greater variety of materials and with greater tool hardness. Although RPBPS costs less per mold these molds produce fewer parts per mold. A downside to RPBPS is the additional finish-machining needed after sintering and infiltration. After such finishing, the mold is tested and released into production. RPBPS can produce a large number of parts per mold before visible signs of wear on the mold cavity. Figure 2-10 illustrates the steps of the RPBPS process. [12, 13]

2.2.2.6 Rapid Solidification Process (RSP)

The Idaho National Engineering and Environmental Laboratory (INEEL) have been developing the Rapid Solidification Process (RSP). RSP typically produces cavity cores with better accuracy, efficiency, lower cost, and shorter lead-time than the typical rapid tooling process. The only difference is that the cavity core fits into a mold frame to produce a complete tool. In RSP, molten metal is sprayed onto a ceramic or polymer pattern. The metal droplets harden the instant they make contact with the ceramic or polymer pattern, forming a cavity core. This process is very fast, efficient, high in resolution and yields high metal properties. However, a major disadvantage to this process is that it is also a line of sight operation, which will not allow for all surfaces to be completely covered. These metal properties are typically even higher than the intrinsic metal properties. Once the pattern has been coated sufficiently, the pattern is removed and the cavity core is machined and fit into the mold frame. Refer to Appendices A and B for a more in-depth look at the technical and business attributes of RSP. Figure 2-11 shows how the RSP tooling process actually works.

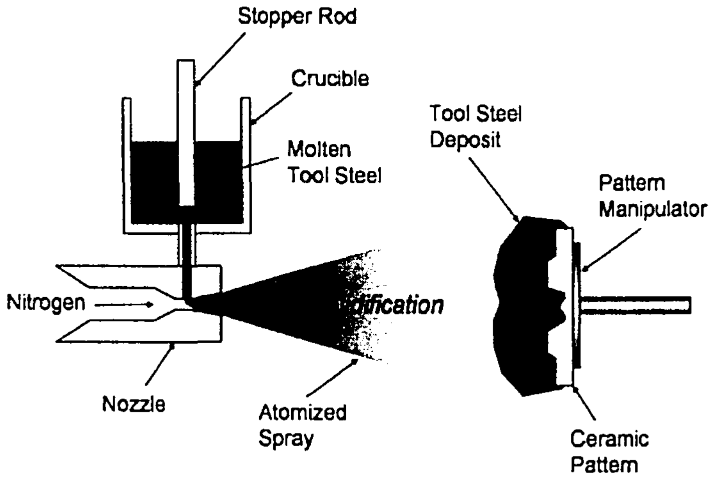


Figure 2-11: Schematic of RSP Tooling Process [14]

Work is presently being done on the accuracy of RSP, as well as trying to increase the applicability to larger patterns. Research is also being done on the feasibility of adding conformal cooling channels to the mold. The one limitation is the inability of the process to reproduce parts with high aspect ratio features. [14]

2.2.2.7 PolySteel^{TM}

The PolySteel^{TM} technique is being developed by Dynamic Tooling. It is capable of producing small to large complex prototype parts, and it can also be used for the production of injection molds with a quick, low-cost lead-time. The process is much like the aluminum-filled epoxy tooling, except the only difference is the material used for tool fabrication. Dynamic Tooling's three materials, PolySteel^{TM} I, II, III, boast zero shrinkage and resultant dimensional accuracy. Refer to Appendices A and B for a more in-depth look at the technical and business attributes of PolySteel^{TM}.

2.2.2.8 RMT Spark

Rapid Moulding Technologies, Ltd. is currently developing the RMT Spark process, formerly known as the SwifTool^{TM} process. This process is similar to the aluminum-filled epoxy tooling technique. The preliminary RP of the product is placed into a molding compound and the parting line is defined. The pattern is then covered with a fiber-filled, thermoset composite material. The part cures for approximately 1 hour and the molding compound is removed. The process is then repeated to mold the second half. After finish machining, the ejector pins and runners then need to be added to the mold.

The net result of this process is a mold, similar to the aluminum-filled epoxy tooling, but slightly more durable. The fabricated mold, assuming that polypropylene is the material to be molded, can produce approximately 50,000 parts per mold depending on the complexity of the part geometry. When an ABS (Acrylonitril Butabyene Styrene) polymer is used, the parts per mold are closer to 1000 to 2000 parts, due to the higher melt temperatures of the ABS. The higher melt temperatures cause more wear on the mold surface, decreasing the life of the tool. Refer to Appendices A and B for a more in-depth look at the technical and business attributes of RMT Spark. [15, 16]

2.2.2.9 MetalCopy^{TM}

The MetalCopy^{TM} technique is a powder-based process developed by the Swedish Institute of Production Engineering Research. Similar to 3D Keltool^{TM}, this process produces tools with high reproducibility, a 99.5% density and 1.5 μm surface finish. An advantage is its ability to produce more than 20,000 parts per tool without significant wear on the tool surface. Depending on the complexity of the geometry, there is a lead-time of approximately two weeks. Compared to traditional tool making methods, this process leads to a 50 percent reduction in tooling costs. Refer to Appendices A and B for a more in-depth look at the technical and business attributes of MetalCopy^{TM}. [16, 17]

2.2.2.10 Laser Tool

Laser Tool was developed with the intention to use a powder-based system that will be sintered layer by layer. Based on the laser sintering process, a metal powder is deposited onto a steel platform by wipers, with a layer thickness of 0.05 mm. A two hundred watt laser beam then scans the surface bed at a scan rate of between 100 and 175 mm/s sintering the metal particles together. A specific disadvantage to this process is that the atmosphere must be controlled and filled with nitrogen. Refer to Appendices A and B for a more in-depth look at the technical and business attributes of Laser Tool.

Typically, sintering causes shrinkage and other minor defects in the part, so when the part is designed these problems must be taken into consideration. The dimensions can be accurately controlled if there is pre-contouring and post-contouring technology used during the process. Because of this contouring, special hardware and software are needed. Due to the need for this hardware and software, this process is one of the least common techniques used. However, the surface roughness of the part ranges between 30 and 40 μm, while having a hardness of 490 HV30 and transverse rupture strength of about 420 MPa. If dimensional accuracy is an absolute must, then an extra step of final grinding and polishing is required. [18]

2.2.2.11 Fusible Metallic Core (FMC)

The fusible metallic core method is ideal for fabricating tools with a complex geometry and hollow sections. No other method presently available concentrates on those two characteristics specifically. The fusible metallic core process is similar to investment casting, except that instead of wax, the material is a low melting point alloy. The tools fabricated using FMC are typically designed as inserts with the internal geometry of the part. These parts are similar to the male mold of the spray metal tooling technique, except that they are suspended in the mold. Once the mold has been filled and the tool is hardened, the core is melted away leaving the desired tool. More research is still needed on this process. Refer to Appendices A and B for a more in-depth look at the technical and business attributes of Fusible Metallic Core. [6]

2.2.2.12 Metal Deposition

The last of the indirect rapid hard tooling techniques is the metal deposition process. There are three different types that are currently being researched. They are 'Spray Metal Deposition', 'Nickel Electroforming', and 'Nickel Vapor Deposition'. Each of the three types begins with a preliminary RP of the product. The RP requires a good surface finish, an incorporated draft angle, and an allowance for shrinkage.

There are two types of spray metal deposition generally used today. The first is Gas Metal Spraying (GMS). GMS uses a low melting point alloy, which passes through a small nozzle above the spraying nozzle to coat the RP pattern. A jet of burning gas melts the metal when the metal crosses in front of the spray nozzle. The melted metal is then atomized and propelled onto the pattern by a jet stream of air that is passed through the same nozzle as the burning gas.

The second spray metal process is Arc Metal Spray (AMS), which is also known as plasma spraying. Both gas metal spraying and arc metal spraying can generate molds that have the capability of up to 2000 parts per mold. They are fast, accurate, inexpensive and capable of handling abrasive materials. Refer to Appendices A and B for a more in-depth look at the technical and business attributes of metal deposition techniques.

The second type of metal deposition tooling is Nickel Electroforming. In nickel electroforming the RP model is sprayed with electrically conductive paint and placed in an acid bath containing bags of nickel powder. Once the part is completely submerged, a voltage is applied to the acid bath. This voltage causes the nickel to attach to the electrically conductive paint surrounding the preliminary RP of the product, which forms the desired tool shape. Nickel Electroforming has a multitude of applications and is currently under-development in order to make it more efficient.

The last metal deposition tooling method is Nickel Vapor Deposition (NVD). In NVD, the preliminary RP of the product in the desired product shape is heated to high temperatures and a nickel carbonyl gas is passed over the pattern to coat it. As the gas is passed over the RP, a layer of nickel is deposited on the pattern and the nickel is adhered to the pattern. This produces an exact duplicate of the preliminary RP. This process, however, has a few disadvantages. The main disadvantage is that NVD is a line of sight process. Much like spray metal tooling, this process cannot accurately duplicate large holes, thin slots or deep caverns. This is because the nickel cannot accurately adhere to those locations without missing parts. [1, 19]

2.2.2.13 EcoTool™

The EcoTool™ process is presently under development at TNO in the Netherlands and at the Danish Technological Institute (DTI). The EcoTool™ process is very similar to the aluminum-filled epoxy tooling technique. The difference, however, is that this process uses a tool steel powder binder system instead of the aluminum-filled epoxy. This binder has flow properties similar to cream and has the ability to harden at room temperature. Comparing the epoxy resin to the powder binder, it is found that the powder binder is more ecologically safe. Another difference is that with EcoTool^{TM}, there is a need for infiltration in order to strengthen the mold. After infiltration, the mold has a tensile strength between 300 and 400 MPa, and a compressive strength between 500 and 600 MPa. One unique aspect of this tooling process is that there have been tests done where glass parts have been made using this mold with little to no sign of wear in the mold cavity.

Tests run on parts molded using EcoTool tools have shown shrinkage levels ranging from 0.1% to 0.3%. The mold has no size limitations, but typical tools produced do not exceed 20 kilograms. It takes, on average, two days to build a typical tool that supports between 10 and 200 parts per mold. This process can be used for many different types of fabrications including injection molding, and high pressure aluminum die-casting. Refer to Appendices A and B for a more in-depth look at the technical and business attributes of EcoTool^{TM}. [16, 18]

2.3 DIRECT RAPID TOOLING PROCESSES

The ability to fabricate a tool directly from a RP machine is the ultimate challenge to rapid tooling. Due to this challenge, there are fewer direct tooling techniques than indirect tooling techniques. Rapid prototyping machines build models with relatively soft materials, which are unsuitable for rapid tooling. Direct rapid tooling, however, produces a tool, which can withstand the high temperatures and pressures typically used in injection molding processes.

Direct tooling has fewer steps in the process than indirect tooling. Direct tooling fabricates the tool directly on the rapid prototyping machine, while indirect tooling requires the fabrication of a preliminary RP of the product first. Direct tooling was meant to further reduce lead times by streamlining the fabrication of tools. An initial goal of direct tooling was to overcome the drawbacks and the problems associated with the indirect tooling methods. Like indirect tooling methods, direct tooling processes can be broken up into two categories, namely, direct soft tooling and direct hard tooling. Figure 2-12 illustrates the classification of the direct soft tooling techniques that are either commercially available or under development.

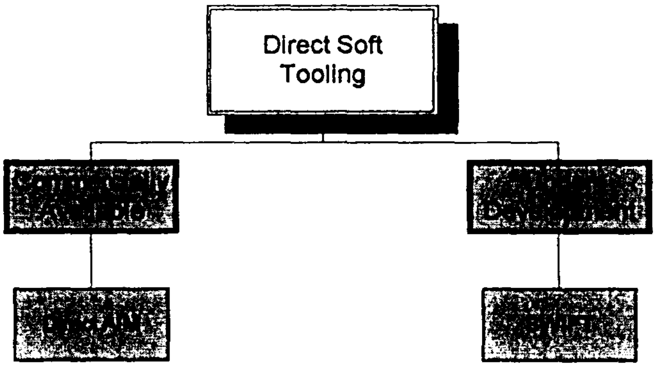


Figure 2-12: Classification Chart of Direct Soft Tooling Techniques

2.3.1 Direct Rapid Soft Tooling Techniques

Direct rapid soft tooling techniques are typically used for shorter production runs. These soft tools are made of a "soft" plastic or non-metallic material. There are two direct soft tooling techniques. They are 'Direct AIM' and 'Solvent Welding Freeform Fabrication' (SWIFT), of which Direct AIM is the most commercially known process.

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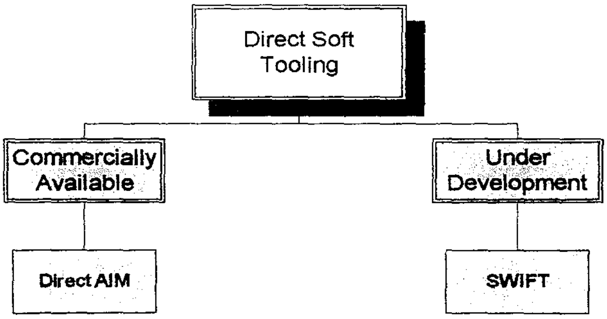

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2.3.1.1 Direct AIM^{TM}

The Direct AIM^{TM} process begins as a CAD model. While the model of the tool is still in CAD, the runners, gates and ejector pin clearance holes are added to the part. Then the pattern is shelled to a thickness of approximately 1.27 mm. Next, the stereolithography machine uses the STL file to build the core and cavity inserts, using a mixture of material and epoxy resin developed by 3D Systems. The most common materials used in Direct AIM are thermoplastics such as ABS, PP, PA66 and PA66 (30% glass filled). Finally, copper cooling channels are inserted into the tool. These copper cooling channels help increase the thermal properties of the tool and help reduce cycle time.

To increase the strength of the tool, a thin layer of aluminum granulate is applied to the back of each insert. A major disadvantage is that the mold demonstrates significant amounts of wear after only a few hundred parts, which is due to the large amount of force needed to eject the part from the tool.

To further increase the strength of the molded part, cycle times can be increased. Longer cycle times allow the material to cool below its glass transition temperature, thereby increasing part strength. Although this is good for the molded part, it is bad for the tool. This increased part strength will decrease the lifetime of the tool. To remedy this problem, cool air needs to be blown over the core to help eject the part out of the mold. The use of a releasing agent on every shot will also help extend the lifetime of these tools. Refer to Appendices A and B for a more in-depth look at the technical and business attributes of Direct AIM™. [5, 6]

2.3.1.2 Solvent Welding Freeform Fabrication (SWIFT)

Solvent Welding Freeform Fabrication (SWIFT) is currently under development. SWIFT is mainly used for short run production. SWIFT tools have a lead-time of between one day to two weeks, depending on the shape and complexity of the part. This process is built one layer at a time. A sheet is fed through a laser printer, which prints a high-density polyethylene to prevent downward facing surfaces from being welded to the scrap material. Next, an acetone solvent is applied to the layer and the sheet is pressed. A shell-milling cutter is then used to mill the thickness of the sheet. The next sheet is fed through the laser printer and the process is repeated until the whole part is made.

A disadvantage to this process is that a traditional milling machine cannot mill undercuts. This process achieves its speed from only milling the required perimeter of each layer, while other techniques need to fill in the perimeter.

The advantage to this process, however, is that the lead-time of the process is about two hours with a cost of raw materials being about one dollar. Tests to date have shown that at least 50 parts per mold can be produced with no signs of wear. There is also a need for generous draft angles and ejector pins. Refer to Appendices A and B for a more in-depth look at the technical and business attributes of SWIFT. [20]

2.3.2 Direct Rapid Hard Tooling Techniques

Direct rapid hard tooling techniques are those that require no intermediate steps to manufacture long-term production tools. Figure 2-13 illustrates the classification of the direct hard tooling techniques that are either commercially available or under-development.

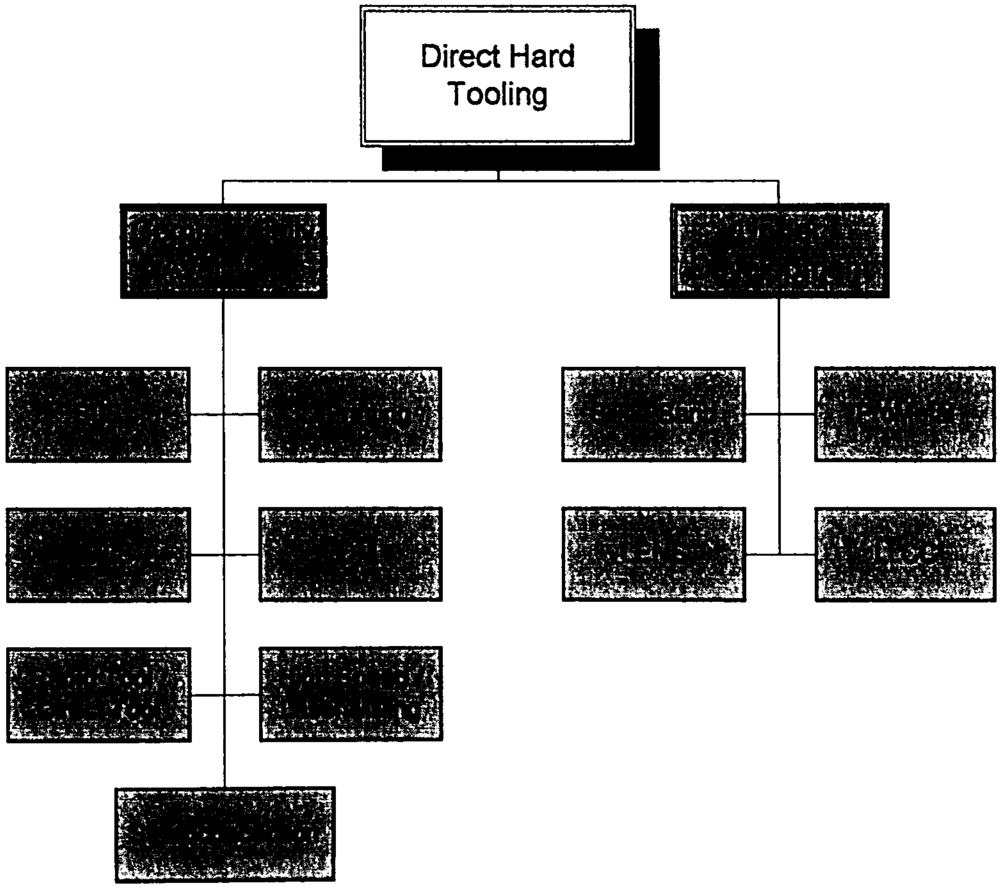

Figure 2-13: Classification Chart of Direct Hard Tooling Techniques

2.3.2.1 Selective Laser Sintering Studies (SLS)

Aside from silica sand, there are other materials being researched for laser sintering. Of those materials, boron and copper are the most predominant. It should

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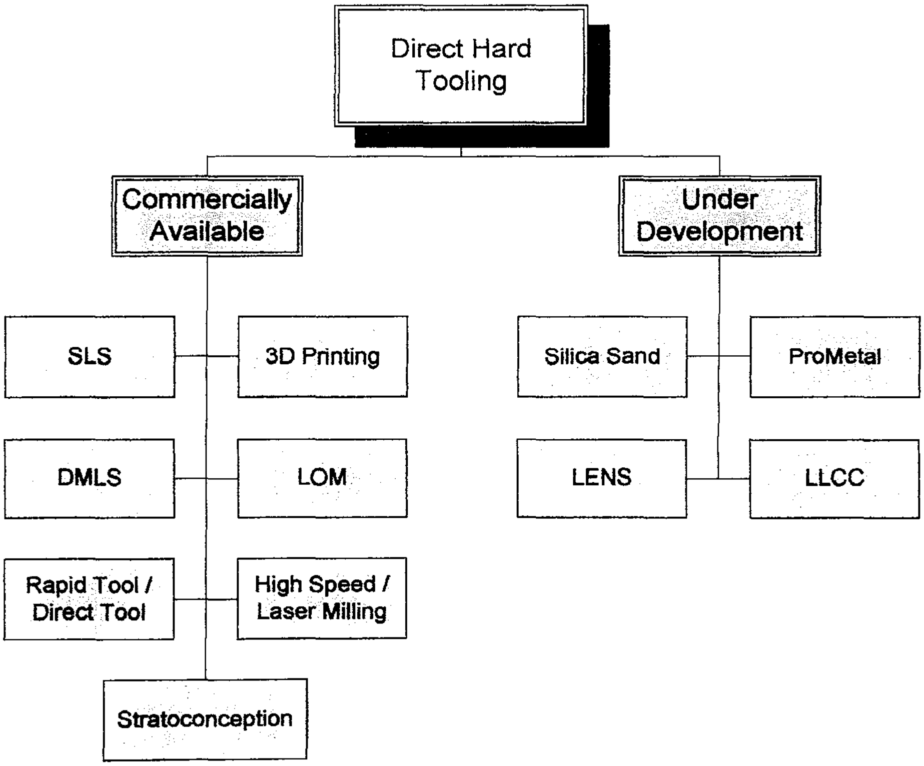


Figure 2-13: Classification Chart of Direct Hard Tooling Techniques

2.3.2.1 Selective Laser Sintering Studies (SLS)

Aside from silica sand, there are other materials being researched for laser sintering. Of those materials, boron and copper are the most predominant. It should be stated that the addition of boron is still in the experimental stages, although some good results have been observed. With the addition of boron, researchers have found that the boron levels need to be maintained at less than 0.4%. As long as the levels are below 0.4%, the additions positively affect the sintering process. Even though it has proved to be an effective aid to the process, if the composition has more than 0.4% of boron the mechanical properties will decrease. It is a highly reactive element and if it is added to a higher loading content, it will start to form compounds with the alloy and decrease the mechanical properties. These extremely hard, brittle borides will be located along the grain boundaries and adversely affect the mechanical properties. [21] Also, the addition of boron will decrease the aging process of the steel, making the steel less desirable.

On the same token, copper can also be used as a structural material during the sintering process. Copper is used because of its good thermal conductivity, high electrical conductivity, and its inexpensive cost. During the sintering process, the liquid binder penetrates the copper particles and arranges the particles into a network, thereby, strengthening the microstructure of the part. A final infiltration with an epoxy is needed to increase the surface finish and to increase the part density. Refer to Appendices A and B for a more in-depth look at the technical and business attributes of SLS. [21, 22]

2.3.2.2 Laser Sintered Metal Tooling (DMLS)

Direct Metal Laser Sintering (DMLS) is a layer-by-layer process that produces accurate tools with little or no shrinkage. This accuracy is due to high power laser sintering and the use of a special non-shrinking steel metal powder. DMLS has a short lead-time of about one to four weeks. This process is suitable for a wide range of tasks, especially for tools requiring good surface accuracy and high detail resolution. The high detail resolution is due to the use of fine-grained powders. This tool is typically used for short production runs and high pressure die-casting.

Currently, research is being done on this process in an attempt to increase the range of abilities of DMLS. Researchers are looking into the optimization of powders to help increase accuracy and achieve better surface finish. "Powders with high packing density, a high flow rate and low oxygen content are preferred." [23]. Still, others are looking at improving surface finish and strength by using plating technology. Refer to Appendices A and B for a more in-depth look at the technical and business attributes of DMLS. [23, 24]

2.3.2.3 RapidTool™ and DirectTool™

RapidTool™ is a selective laser sintering process from 3D systems, which uses a polymer-coated steel powder. It is often thought of as a bridge tooling process, which "bridges the gap" between the hard and soft tooling techniques.

The RapidTool^{TM} process starts by producing a "green" tool using a laser fused binder to hold the steel particles together. Next, the "green" tool is transferred into a furnace to eliminate the binder, then sinter the steel powder, and finally infiltrate the tool with copper to provide extra strength. It should be noted that in addition to the increase in strength, infiltration increases the density and reduces the total shrinkage.

The main advantage to RapidTool^{TM} is the direct fabrication of the metal part to be used as a core or a cavity insert for injection molding. A major disadvantage of RapidTool^{TM}; however, is the stair-stepping finish that is obtained, which would warrant post finishing operation.

Furthermore, two new materials were developed for the RapidTool^{TM} process. These two materials are 'LaserForm^{TM}' and 'copper polyamide (PA)'. There are only few differences in the process due to these materials.

When the LaserForm^{TM} material is used, the sintered "green" tool is infiltrated with bronze at an oven temperature of 1070°C. Once the oven cycle is complete, the completed tool will have a composition of 60% stainless steel and 40% bronze.

However, the copper-PA material does not require a furnace cycle. In the place of the furnace cycle, an epoxy is used to seal the surfaces. The tool is then sanded and backed with a metal alloy. The use of this material reduces the cycle time and produces 100 to 400 parts per mold.

The EOS DirectTool^{TM} process is similar to the RapidTool^{TM} process, except that DirectTool^{TM} requires a special machine. Also, the molds that are produced are porous and usually need to undergo an infiltration with an epoxy resin in order to increase strength. [6] The final mold also requires finish polishing. The main use for this process is to produce complex inserts and for parts with surfaces which cannot be machined directly. Refer to Appendices A and B for a more in-depth look at the technical and business attributes of RapidTool^{TM} and DirectTool^{TM} .[5, 6]

2.3.2.4 3D Printing

This process was developed at MIT in the early 1990's, and has since been licensed to six companies. 3D printing was developed for the rapid and flexible production of prototype parts, end use parts and tools directly from a CAD model. [25] The main difference between 3D printing and the other techniques mentioned above is that 3D printing can be used for any geometry and material, while the others have limitations on geometry and materials. The CAD model is first sliced into layers, then the tool is built up layer-by-layer, and, finally, the layers are carefully laid down on a lowering platform. Applying binder in the desired locations to form each layer is similar to an inkjet printer. In order to remove the unnecessary support material, the tool is heat-treated and the tool is finished.

3D printing has the versatility to form anything that can be drawn in CAD, assuming that the excess powder and support material has a way of getting away from the part during the heat treatment. The most favorable characteristic of this process is the ease of control over the material composition.

3D printing has been the leader in the use of ceramics and metal for rapid tooling. Reportedly, this process greatly reduces the time-to-market, enhances product quality and most importantly reduces tooling costs. Some of the applications of 3D printing are listed below:

- Ceramic Shells for Direct Casting of Metal Parts
- Structural Ceramics
- Direct Metal Tools
- Composite and Functionally Gradient Parts
- Medical Applications
- Porous Ceramic Filters
- Appearance Models
- Experimental Geometries

Two major disadvantages restrict 3D printing. First, the tool can only produce a small number of parts per mold before showing signs of wear on the surface of the tool. Second, finishing operations, such as grinding and polishing, are needed to achieve the desired surface finish. A few advantages, however, are the reduced cycle times, the presence of conformal cooling channels, if desired, and a fully dense tool. It should also be noted that 3D printing could only produce about 40 parts per mold, which in comparison to the other processes is quite low. 3D printing can also be used as a hard tooling technique. Refer to Appendices A and B for a more in-depth look at the technical and business attributes of 3D Printing. [25].

2.3.2.5 Laminated Object Manufacturing (LOM)

Laminated object manufacturing (LOM) was developed by Helysis Corporation and is now owned by Cubic Technologies. When it was first developed, the primary material was paper. Originally, the main uses for this process were the fabrication of prototypes and casting models. Since then, it has grown to include metals. This process involves using modified Helysis 1015 or 2030 machines. These machines use a type cast powder metal or a ceramic sheet, which is cut by a laser, and stacks the layers together. Once the layers are stacked together, the resultant tool is placed into a furnace, and sintered to bind the layers together.

In 1996, a process known as the 'Lastform programme' began as an attempt to develop a method of manufacturing dies for a wide range of aerospace and automotive processes including metal pressing, resin transfer molding and injection molding to name a few. [16] This process shows potential of time saving and improved process efficiency. In addition to the produced tool, conformal cooling channels are added to further reduce the cycle time per mold. This process is typically used for larger molds in the aerospace and automobile industry. An advantage to LOM is that it is capable of little or no material loss. Another advantage is that the material used is standard sheet metal. The disadvantage to this process is that it requires special software and hardware. Not much has been found on this series of testing, but results should be available soon. Refer to Appendices A and B for a more in-depth look at the technical and business attributes of LOM. Figure 2-14 illustrates how the LOM process works. [16]

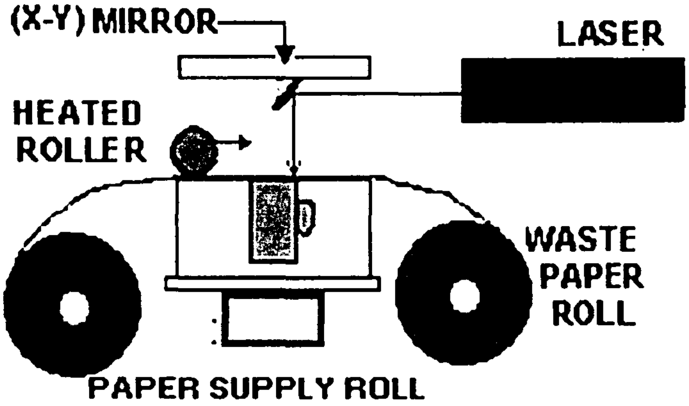


Figure 2-14: Schematic of LOM Process [16]

2.3.2.6 Laser and High Speed Milling

Two very similar Direct Rapid Hard Tooling techniques are 'laser milling' and 'high-speed milling'. Both of these techniques are limited to line of sight and the degree of angle of the cutting tool. There are, however, a few differences.

Deckel Maho Gildemeister of Germany developed the 'laser milling' technique. This process uses a non-contact technique enabling sharp and straight cavity corners, which are hard to achieve with conventional techniques. This process also allows for the use of many different materials, especially ceramics. The drawbacks to this method; however, are the limited angle of inclination, limiting it to a geometrical freedom of about 20°, the width-to-depth ratio is limited to 1:2.5, and the process creeps along at a pace of about 2cc/hour, maximum.

Opposite the slow meticulous process of 'Laser milling', is the 'high-speed milling' process. Here, the process is done using high-cutting speeds, high rotational speeds, high feed rates, and small diameter mills. The combination of cutting speed and small diameter of the milling cutter allows for accurate and smooth cavity cuts. The mill cutting diameter is typically less than 25 mm and the spindle can vary from 15,000 – 40,000 rpms with a max speed of 160,000 rpms. Refer to Appendices A and B for a more in-depth look at the technical and business attributes of high-speed and laser milling. [18]

2.3.2.7 Stratoconception

The 'Stratoconception' technique is commercially available in France by Cirtes. This technique is ideal for rapid tooling because it reduces time to market by utilizing concurrent engineering. This technique takes a CAD model and manufactures it layer-by-layer without any lag in design or manufacturing. The process is a combination of computer calculations and user input. Once a STL file is generated the computer takes control. First, the cutting plane is determined, taking into account the layer thickness, precision, and surface ratio for each layer. These layers are called "Stratum". Next the computer calculates where the stiffeners and straightening plugs are needed. Once these calculations are made, the CAD file is shown on the screen with the layers outlined. Upon acceptance of the calculated layer thickness, precision and orientation by the user, the tool paths are generated, tools are chosen, and the profile optimized. Next, the profile of each layer is determined and cut from the material. The typical materials used in 'Stratoconception' are treated and untreated steels and plastics. Depending on the material used and its properties, the cutting is done mostly by laser or water jet. Once all the layers are cut, the tool is assembled using the geometric inserts for alignment. These parts are used to help understand the mechanical properties, limits and potential production problems.

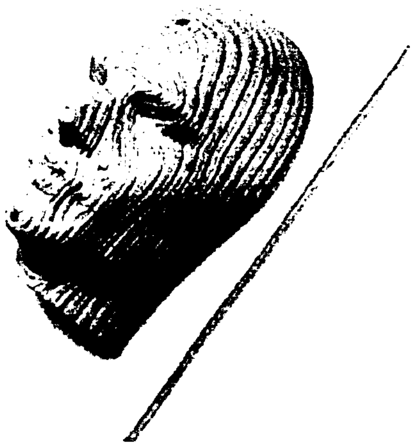


Figure 2-15: A tool made with the Stratoconception Technique [26]

This fast process has no limitations on shape, material, or size. This process is especially good for parts with undercuts, or hollow parts where other techniques fall short. With 'Stratoconception', the time-to-market is reduced by about 25 to 30 percent depending on the complexity of the shape. Foundry, plasturgy, and metal forming are the three main applications for this technique. Figure 2-15 demonstrates a model of 'Stratoconception'. An idea of the layer thickness can be seen in the figure indicated below. Also, notice the detail that is achievable with this process. Refer to

Appendices A and B for a more in-depth look at the technical and business attributes of 'Stratoconception'.

A process called Strato-hard metal is currently under development at the same company. This process is very similar in nature to 'Stratoconception'. The main differences, however, are in the better regulation of material temperature, gas release during the process, and a large savings in weight. The company has not yet posted much data on this method, but claims that this adapted version of 'Stratoconception' will have a short lead-time and large cost reductions. [18, 26]

2.3.2.8 Laser Sintering of Silica Sand

Laser sintering of silica sand was developed to assist in sand cast-molding, at the National University of Singapore. Sand is being studied because the foundry industry is the primary user of this technology. A unique property of the silica sand technique is that the material, silica, is actually made of 18 different materials. Of these 18 materials, four materials act as the binding material holding the sand together. These four materials, aluminum, calcium, magnesium, and chlorine, have a lower melting point, which causes the materials to liquefy before any other materials in the silica and thereby binding the materials together.

Tests were done on different processing parameters such as the scan speed and the laser power applied to the part. It was found that a laser power of 80 W and a scan speed of 100 mm s^{-1} demonstrated the best results. With these parameters, the layer strength was good and the surface finish was the smoothest.

After the laser sintering process, an infiltration step is needed in order to increase the strength, surface finish and density of the tool. During the infiltration process, a special formula is painted on the tool and then baked in an oven at 200°C. Only mechanical strength of the tool was greatly affected by this infiltration.

Once every step of the process is complete, the total time to mold completion is approximately 22 hours. The lead-time, however, is only accurate for a part of relatively small dimensions. The dimensional accuracy is good, with a low surface roughness value of about 25.4 μm. Compared with conventional fabrication processes; the sand-casting mold process reportedly reduces errors arising from pattern fabrication, although these errors can be controlled within an acceptable range. Refer to Appendices A and B for a more in-depth look at the technical and business attributes of Laser sintering of Silica Sand. [27]

2.3.2.9 Laser Engineered Net Shaping (LENS)

Sandia National Laboratories originally developed 'Laser Engineered Net Shaping' (LENS). This process requires special equipment that can be purchased directly from the company Optomec Inc. LENS can create metal tools directly from CAD files using materials such as 316 steel, H13 tool steel, tungsten, and titanium carbide cermets. Much like RP, the LENS process is also an additive process. Each layer is melted, injected with metal powder, and then solidified. Comparing a tool from LENS to a tool from sintering, a LENS tools has better mechanical properties than a sintered tool. This is due to the fact that the tool becomes fully dense as it is built and not after it is sintered. When tools are sintered they are apt to shrinkage, whereas, the tools in LENS do not shrink.

The advantages to this process are the superior mechanical properties, the ability to make complex tools, and the reduced post-processing requirements. The disadvantages, however, slightly outweigh the advantages. This process is limited to a small number of materials and the unit has a large physical size requiring a large area to house the equipment. Lastly, the unit has high power consumption due to the high laser wattage. Refer to Appendices A and B for a more in-depth look at the technical and business attributes of LENS. [28]

2.3.2.10 ProMetal™

Extrude Hone developed the ProMetal™ technology. This process is based directly on MIT's 3D Printing technique. ProMetal™ print heads deposit droplets of binding solution on the powder, which is spread by a similar print head that sweeps across the lowering table. The binder droplets only fall on desired locations, bonding each layer until all cross-sections have been built. The result is a precision-made tool that possesses unparalleled resolution.

Figure 2-16 is a diagram of the process of ProMetal™. The ProMetal™ process begins with a CAD file and is then built using 3D printing technology. Following the completion of the build, the tool is placed in a furnace and sintered and infiltrated to achieve full tool density. This process offers the advantage of good mechanical properties. The parts final composition is approximately 60% steel and 40% bronze. There is a considerable amount of finishing required for a good surface finish; however, these molds can be used to make hundreds of thousands of parts with almost any plastic. Refer to Appendices A and B for a more in-depth look at the technical and business attributes of ProMetal™. [18, 29]

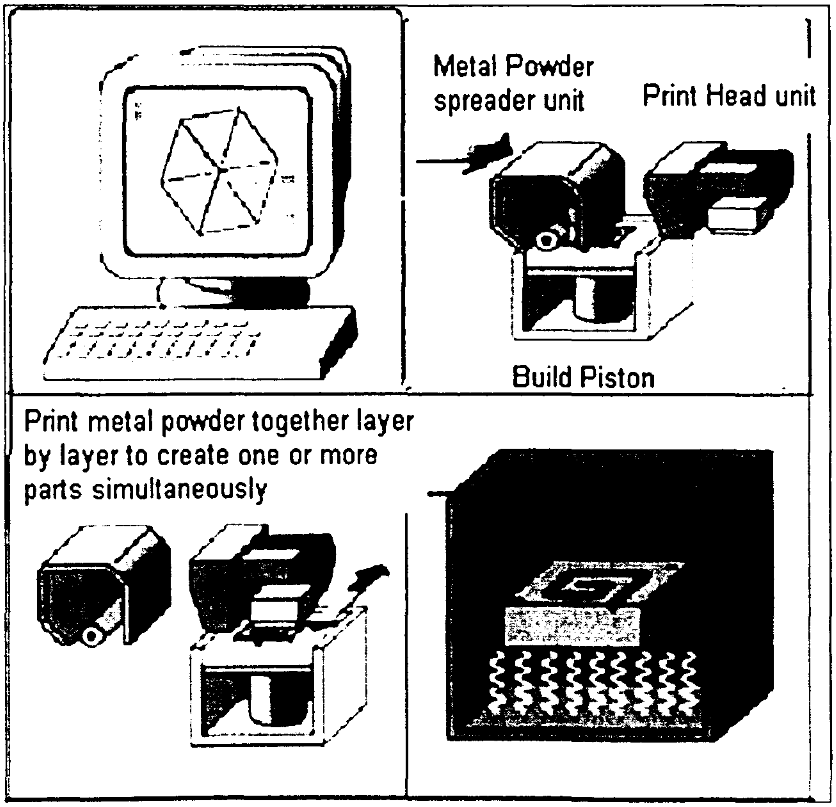


Figure 2-16: Diagram of ProMetal™ Process [29]

2.3.2.11 Laminated Laser Cut Cavities (LLCC)

'Laminated laser cut cavities' (LLCC) were originally developed by CRID. The process is similar to the laminated tooling process, where the thin metal sheets are cut to form by high power CO_2 lasers, stacked, and then assembled to produce the required cavity. This process is mainly used for parts greater than 250 mm and is made using thermoplastics. The parts produced are able to withstand very high temperatures and high pressure conditions. CRID claims that this process can have a cost reduction of up to 65%, assuming the surface aspect is not an issue. On the same token, if the surface aspect is necessary, the cost reduction is not so dramatic. Refer to Appendices A and B for a more in-depth look at the technical and business attributes of LLCC. [30]

2.4 MATERIAL ADVANCES

Standard rapid prototyping materials cannot be used for most cases anymore due to the nature of rapid tooling and the need for multiple part production cycles per mold. There have been many advances in material research over the years in an attempt to find better suitable materials to assist in the success of rapid tooling. The Institute for Polymer Testing and Polymer Science (IKP) and the Fraunhofer Institute for Chemical Technologies (FhG/ICT) have done a large amount of research in this area. Depending on the need for production, the metal tools are reliable for small production batch sizes, but the use of resin is much cheaper, faster, and often times more accurate. Most importantly, the process variables such as cooling times and cycle times play a huge role in the decision of what material and process to use. One company even suggested the union of two different techniques to achieve the best quality product possible. Tests have been done on a few of the more common processes used today, such as '3D Keltool^{TM}', 'Metal Spraying', 'Investment Casting', 'Powder Based' techniques, and 'Cast Resin' Techniques.

In the case of 'metal spraying,' currently these processes use low melting temperature alloys. This is because of the cheap cost and its ability to mold thousands of parts with one mold. The most important factor in the selection of the proper alloy is the thermal properties of the rapid prototype's material.

'Rapid Steel' is primarily used to create steel/copper mold inserts and to help save money and time. This material offers a steel hardness of P20, durability, high thermal conductivity, and wears like traditional tool steels generating over 100,000 parts per mold. This material is used in the selective laser sintering process. A few disadvantages to this material are that it can be expensive and has a huge potential for secondary finishing.

'Investment casting' uses rapid prototype patterns as "lost models" because the patterns are dissolved at the end of the process. Two types of RP molds are produced in one from a stereolithography process, and the other from laser sintered polystyrene and polycarbonate. Some of the issues run into using these processes are shrinkage of the pattern during the process, thick walled part thermal expansion causing internal stresses, and surface failures of the patterns. To solve these problems, materials with a smaller particle size, such as the True Form material from DTM, can be used.

In some cases, powder based processes such as '3D Keltool™' and 'metal laser sintering' processes working with silicone rubber molds and polymer binders, respectively, can be used instead of investment casting to achieve better parts. In both cases, a furnace step is required to increase the strength of the parts and to fill the porous structures.

Copper polyamide is another possible material that has been developed to use in a mold for short production runs of production equivalent plastic parts. This material, developed by DTM, is a thermally conductive composite of copper and plastic. An advantage to this material is that it is suitable for injection molding using polyethylene, polypropylene and glass filled polypropylene, polystyrene, ABS, PC/ABS, and other common plastics. Copper-polyamide has a lead-time of about four days, and allows for ejector pins, runners, gates, cooling channels, and sprues to be built right into the part. Despite all these advantages, this material is very expensive.

Polymer-tooling inserts are considered more often than other tools because of the cost savings that tooling inserts provide. The setbacks to these inserts, compared to the previously mentioned processes, are the lack of strength and low thermal stability. Research has shown that the use of cooling channels is feasible, but ineffective; and therefore, the cycle time is increased because of the inability to decrease the cooling time of the parts.

Using cast resins as a test bed, it was found that the addition of aluminum increased the mechanical strength and the thermal conductivity of the mold inserts. Other materials were added to the resins in an attempt to increase mold strength. However, aluminum is demonstrating the largest increase in mold strength. The use of material filled resins is helping polymer tooling become a competitor of metal tooling processes, but more research is needed before it is a true competitor.

Another molding material known as 'Cibatool-Express™ 2000', has been specifically designed for tools possessing high strength and excellent thermal resistance. This material produces accurate molds, with little or no finishing required at a very fast rate. A major setback to this material is the inability to produce complex geometries or, if a problem occurs, it is difficult to refill or fix. [23, 31, 32]

2.5 SELECTING THE RIGHT PROCESS

Selecting the right process depends on a number of different variables and is a very complex decision. Every detail about the desired outcome needs to be known. Questions such as, can a generic material be used? Does it need to be the final product material? How accurate do the surface finish and the geometry need to be in the part? What are the properties of the material being injected into this mold? What kind of lead-time is expected? These are only some of the questions that need to be answered when deciding on the right process. One important factor to keep in mind is that while direct RP tool generation may have the fastest lead time, one of the indirect tooling methods might offer a slower lead time but a cheaper, more accurate resultant tool.

Selecting the right process at this point in the development of tooling can make or break a company. So, in-order to meet this goal, every factor of each process needs to be evaluated and compared to the desired outcome, before the final decision is made as to which is the right process for the project. A complete diagram of the many rapid tooling processes discussed in the report can be found in Appendix C. Also, for a good comparison of the entire process field, please refer to Appendices A and B, which compares different processes side by side separated by the technical and business attributes.

2.6 PROCESS DIAGRAMS

Process diagrams are a very useful resource when selecting the proper technique. These diagrams illustrate the process itself from idea generation to finished tool, along with its respective technical attributes and business attributes. While assisting in selecting the right process for a specific application, these process diagrams also help to understand each technique.

Each of the above technique's process-steps are presented in flow-chart type fashion in Appendices D, E, and F. Appendix D. Process Steps for each Technique is a spreadsheet with each technique's steps written out. Appendix E. "Wiring" Diagram starting CAD Model of Product and Appendix F. "Wiring" Diagram Starting CAD Model of Tool can be termed as a "wiring" diagram format showing all the techniques process steps side-by-side, which required classifications or simplifications of the steps.

2.7 SUMMARY

In short, the field of rapid tooling hasn't quite caught on in the large scale. Many companies are still skeptical of the need for rapid tooling, but it is slowly catching-on as companies look for ways to save money and time. Currently, the majority of molds are still made using subtractive fabrication, or production molding. The idea of rapid tooling, however, isn't to completely replace production tooling, but to work in conjunction with production tooling. Rapid tooling processes are used to identify molding problems, produce market test specimens, and for short production runs to make up for the delay in production.

Rapid tooling has evolved from rapid prototyping and extends the benefits of reduced cost and time to the crucial area of prototype and functional product tooling. Unfortunately, it is not possible to recommend one tooling method for all applications, for each has its advantages and disadvantages. The field of rapid tooling will continue to grow as companies and universities increase the productivity, strength, durability, lower costs, and reduce lead times to make better processes.

Rapid tooling has gained attention in many other fields than originally anticipated, which range from motor vehicles, to consumer products and also to academia. "This strong and consistent growth in sales and the widespread use of the technology, present very optimistic prospects for the future of rapid manufacturing". [32] The next step is to use this information in an expert system to help identify the appropriate technique to use for each application.

3 BACKGROUND OF EXPERT SYSTEMS

3.1 WHAT ARE EXPERT SYSTEMS

In its most basic meaning, an expert system is a solution to programming artificial intelligence. Expert systems, along with artificial intelligence became popular in the late 1970's and a significant amount of research has been done in both areas. An expert system can be defined as "an intelligent computer program that uses knowledge and inference procedures to solve problems that are difficult enough to require significant human expertise for their solutions." [33]

Expert systems were designed to replace the human experts that currently solve problems. An expert is a person who is very knowledgeable and skilled in a certain area. These experts solve problems more efficiently than the common individual. The early 1970's saw the first expert system developed. These first systems relied entirely on the knowledge of the expert writing the program. As research has continued, expert systems have become more intelligent and can solve more complicated problems.

An expert system can solve a function which would need a human expert, or it can act as an assistant to human experts. For example, when having computer problems, a customer will call the support staff and through a series of questions the staff will be able to pin point the problem. The expert system in this case, is the questions and respective answers which then narrow down all the possibilities to achieve the solution. Even with these computer run expert systems, getting the correct interface between human and machine is the most common problem in getting these programs to work effectively. The typical tasks of an expert system can involve, but are not limited to:

- the interpretation of data (such as sonar signals),
- diagnosis of malfunctions (such as equipment faults or human disease),
- structural analysis of complex objects (such as chemical compounds),
- configuration of complex objects (such as computer systems), and
- planning sequences of actions (such as might be performed by robots). [34]

Currently there are non-expert system programs that can perform these tasks and don't require special software. However, the expert system is exponentially better and more accurate than any of these alternate programs. There are so many different capabilities of expert systems that they can be applied to almost any application. The list above is simply a sampling of the possible tasks that an expert system can perform. There are some characteristics of expert systems that are common to all of the systems.

Each expert system inspires human reasoning, performs reasoning sequences and solves problems by heuristic methods, not analytical techniques. These three characteristics differentiate expert systems from other and more conventional reasoning methods.

The first characteristic, inspiring human reasoning, demonstrates the ability of an expert system to solve problems beyond the knowledge of the expert. The program utilizes the solving techniques of the expert, and builds on them to solve the problem quicker and more accurately. The expert system will not only use mathematical or analytical methods to solve problems, but begin to "think" like a human and use deductive reasoning methods.

The main function of an expert system is to reason the solution by using its knowledge base. There are two main parts to an expert system, the knowledge base and the program. These two parts are kept apart because the knowledge is typically input into the program in a specific form, and then the program is written to search through the spatial information to determine the appropriate answer. This is the reasoning characteristic of an expert system.

The last characteristic of expert systems, heuristic analysis, demonstrates the previous two characteristics in action. This characteristic builds on the knowledge base by identifying "rules of thumb" to govern a large group of information. These rules will then be used to help the programs run quickly.

There are a few characteristics which will help differentiate between artificial intelligence and expert systems. Expert systems are able to run quickly and accurately, solve problems that would typically take a large amount of human knowledge, and are capable of explaining the reasoning behind a specific answer. Artificial intelligence programs do not run quickly and do not always output the correct answer. For a program to be a true expert system, it must be faster and more accurate than a human expert.

A major difference between artificial intelligence (AI) and an expert system is the ability of an expert system to solve "real world" problems based on its knowledge base and rules. AI, however, can only concentrate on abstract ideas to learn the rules that an expert system uses, and then the AI can mathematically solve the solution. The answers are typically incorrect and often take a significant amount of time.

The last difference between AI and expert systems is the ability to explain the answer and the reasoning used. Expert systems are designed to explain the solution so as to convince the user that the answer is correct. An expert system can be written for any number of applications, as stated before, which means that there will be a wide variety of people using the software. These people need to be able to depend on the expert system to give the right answer, so therefore the explanation of the answer is necessary to prove itself. Since AI is typically used as a research device, a limited number of people will use it, so the explanations of the answers are often not as necessary. The mind set of an expert system developer is to set up the software so that whoever uses it can be confident in the solution. On the other hand, the person developing the AI program is the person who will be using the software, so he or she knows how it works and how the AI program is obtaining its answer.

Building an expert system requires three key steps. The first step is the knowledge acquisition. It is here where the base knowledge is gathered and interpreted by the developer. Knowledge acquisition is described as "the transfer and transformation of potential problem-solving expertise from some knowledge source to a program." [34] This knowledge is collected from the human experts and then input into the system in a special format. The information is typically collected by interviews and extensive research by one or several individuals. This information is then taken to a "knowledge engineer" who will interpret the collected information and write the information into a specific format for the system to understand and manipulate. This is the most important step in the development of an expert system because if any information becomes inconsistent the whole system will stall.

It is in this step that the knowledge engineer must ensure that the information is consistent across the board so that the program runs smoothly. One of the most common problems with collecting data is that the experts all have their own slang for certain components or processes. It often takes a very in-depth look at the information gathered to ensure that information that might be presented differently doesn't actually mean the same thing. For example, two experts explaining the same topic go into great detail of the process. The first expert explains the process from start to finish in simple terms; however, the second expert explains the whole process in technical terms making it very difficult to understand. It is these differences which make the knowledge acquisition step very difficult and time consuming.

A second issue with knowledge acquisition is the ability to represent all the information in great detail. This means that while the general idea of a process is known, the principles that guide the process along are unknown. For example, if a technician sees that a machine has broken down, he can tell you exactly what can cause these break downs and where the main problems are, but he cannot tell you how it happens or how often these problems will occur.

Another issue with this step is that most experts obtain their knowledge through experience. The idea of "learning from your mistakes" is typically not a trait of an expert system. An expert can tell the knowledge engineer how to fix a specific problem and what works in most cases, but it is in the cases which don't have a prior experience where the system runs into problems. The expert system relies mostly on the base knowledge and the developed rules, not on experience.

The second step is taking all of the acquired knowledge and determining a way of representing all the information in common groups. Representing data can be easy or difficult, depending on the data collected. The information must be sorted into groups which have common traits and relationships. Then these groups are given a specific symbol or characteristic title so that the program can understand the relationship between group A and group B. The better defined the groups; the easier it is to pull information from each group quickly. In most cases, symbolic notation is used mainly because it is much easier for computers to understand. For example, if the data collected was as listed below:

- Apple : red, smooth,
- Orange : Orange, squishy
- Leaf : green, rough

After inspecting the data, it was determined that there are two classifications that the three objects fall into, color and feel. These two classifications allow the system to accurately compare the apple, orange, and leaf together, as seen below in Table 3-1. A more in-depth look at knowledge representation can be found in sections 3.3 and 3.4 of this chapter.

Once the data is accurately represented, the process of using the data has to be determined. An expert system can use a number of techniques to "page through" all the information gathered, and some techniques are better than others. There are basic knowledge representation techniques: forward or backward chaining, hypothetical reasoning, or explanation facilities. These are just a few of the different techniques used to obtain a result of a specific problem. This paper will only touch on the technique that was chosen during research due to the large number of techniques used to solve expert systems.

Color	Feel
Red, Apple	Smooth, Apple
Orange, Orange	Squishy, Orange
Green, Leaf	Rough, Leaf

Table 3-1: Data Classification

3.2 BRIEF OVERVIEW OF ARTIFICIAL INTELLIGENCE

None of the expert system technology would be possible without the use of artificial intelligence (AI). AI is the basis for expert systems. By definition, AI is a "branch of computer science dealing with the simulation of intelligent behavior in computers, and has the capability of a machine to imitate intelligent human behavior." (Webster's Dictionary) This means that computers are designed and programmed to do things that humans do. The difficulty in programming computers to do human tasks is that humans have the ability for judgmental reasoning, perceptional thinking and a large amount of memory. It is also difficult to program a computer to learn from its mistakes, however with AI, this is becoming possible.

In its most basic form, AI is a human emulator. The AI systems are designed to perform all the tasks that a human can do, but much more efficiently and accurately. Humans have problems with extremely involved calculations while computers do those types of problems very easily. AI has the ideal human thought process and does things in the proper manner without using shortcuts. Even though computers will typically do things the "long" way, they are much faster than any human; this is what makes AI so popular.

Artificial intelligence began as a game playing device and later became the theory proving machine that it is today. When AI was first introduced, it was being used to program games to run without needing an opponent. For example, computer games which play zero players, meaning no human interaction. A game like chess would be played by the computer until the computer has beaten itself. Another form of AI would be playing a typically two player game as a single player game. If you were to play the same chess game, you could play the computer and the computer would be able to react to your movements and move accordingly. This form of AI is very simple compared to some of the other things it is used for today. AI is used as a classification tool which allows users to determine which type of animal a lion is for example. This is a basic use for AI now, but the most powerful uses are governmental applications, which are top secret. AI is typically used as a method of representing knowledge for use in expert systems.

3.3 KNOWLEDGE REPRESENTATION

As stated before, the most important step in developing expert systems is to determine a way of representing all the useful knowledge that was gained through interviews and in-depth research. While being the most important step, it is also the most difficult process because the better the representation the better the system runs.

The best source of information is the experts themselves. However, getting information from them can be difficult. Often times, experts have been using a particular process for such a long time, it has become second nature to them. This makes it difficult for them to explain what they do. A good example of this is riding a bike. Most people are taught how to ride a bike at a young age, and then through the years of practice, it has become second nature. So now when a child has ridden a bike for long time, they couldn't really explain how it works or how to ride a bike.

Therefore, when collecting data, the interviewer has to be patient and ask questions that will probe the expert causing the expert to recall certain things that can help explain the process in question.

Another reason for the difficulty in collecting data is that technology and information is changing every day. Technology, for example, is constantly being improved and because of this experts have difficulties keeping up to date on technology which will in turn cause them to lose track of the previous techniques. This can be stressful and often times experts will not set up interviews with people to learn the process, because they are so busy keeping up themselves. This causes information to get lost or never be recorded.

Since the knowledge representation step is very important, it is important to be very organized. Organization will help the programmer identify similarities between information and apply the information to the program. The best way to organize the data is to index, file, or label everything in such a manner that it would take someone a very short amount of time to get the desired information. Having all the information organized will help the programmer organize the data in the expert system which in turn helps the system run quicker and more accurately.

Once the organizational scheme has been determined, then the programmer has to ensure that the computer program will be able to accept and utilize the information. If the computer doesn't except the organization scheme, the programmer simply needs to program the system to recognize the new scheme. This is a very easy step because "many representational schemes that appear to be distinct can be shown to be formally equivalent." [34]

There are two main characteristics of knowledge representation, and they are syntax and semantics. Each of these characteristics is very important since the computers rely heavily on both of them. The syntax simply refers to a set of rules for relating the information and the organizational scheme language. While the semantics refer to how specific information within the database should be understood. Without proper syntax and information semantics, expert systems will not run efficiently or accurately.

The best way to increase the accuracy and the efficiency of the expert system is to have the expert write the program. Presently, most expert systems are developed by people who are second or third party to the information. This means that they are told how things work and how things need to be, but when it comes down to the fine details, the only person completely comfortable with the information is the expert. Especially during the trouble shooting stage of development, an expert will know exactly what is happening when the correct answer is being output; therefore it is corrected right away. When a second or third party developer is troubleshooting the problems, it will take a significant amount of time to complete, because they have to identify the problem and then figure out what is wrong with it. This means more conversations with the experts and/or more research.

There are many different techniques to represent and utilize data within an expert system. Some programs use what is called a depth-first approach, while others use a breadth-first approach. In a depth-first approach, the user will ask for a certain relationship and begin running the program. The expert system will then search the entire database for matches of the first part of the relationship. Once it has reached the end of the database it moves on to the next part of the relationship and cancels things out as they don't match. On the other hand, in the breadth-first approach, the expert system will find a match to the first part of the relationship and check if the next part of the relationship is satisfied, if not it continues on. If it does match, it checks the next part of the relationship until it has reached a match. Either technique work equally well, with the main difference being speed. The breadth-first approach can be faster for some applications while the depth-first approach can be faster for others. It really depends on the application that the expert system is being used.

Another possible technique is the use of schematas. These schematas are based on the previous two techniques, but have the ability for a more complex knowledge structure. This technique is used to help an expert system learn from mistakes. An expert system can be taught to continue with positive outcomes and never repeat any negative outcomes. This means that when a system calculates an answer in a long, ineffective manner, it won't try that process again if a similar question is asked. The computer will continue to use the good process until it finds a problem with that process. A second type of schemata is the conceptual schemata. With this type of schemata, general properties distinguish between objects. This allows a program to remove human expert bias and correctly identify objects that a human may identify incorrectly. These conceptual schematas allow computers freedom from stereotypes and bias which are prominent in humans.

A third technique in knowledge representation is to use frames. A frame is a type of relationship used when there is a large amount of common knowledge about a specific object. For example, all computers have mother boards, monitors, keyboards, cooling fans, hard drives, etc... Although all computers have these characteristics in common with each other, there are many different brands, sizes, component capabilities. The frame is the default setting of an object and each of the categories has a specific answer. It is these answers that the computer will search through to get the output that the user wants. Table 3-2, below, is a frame for a Dell computer.

Manufacturer	DELL
Model	Inspiron 600M
Processor	Intel Centrino 1.6 GHz
Hard Drive	40 GBs

Table 3-2: Frame Example

These techniques are all good ways to represent information. Each technique has its benefits and its disadvantages, so it basically comes down to using the technique which is the most appropriate for the application. Some representations work well for some applications and some shouldn't even be considered.

As can be seen in the previous section, there are plenty of ways to represent the knowledge base. The symbolic representation is a good way to relate different groups of information to each other. The most common symbolic representation involves using logic. Logic is the set of rules used by the computer for performing reasoning tasks. Logic is the engine that drives the expert system. These expert systems are built using logic as the uniform language.

3.4 RULE-BASED SYSTEMS

As with everything else in the world, rule-based expert systems are run by sets of rules, either programmed or learned. These rules guide the expert system through its execution. At the root of every expert system is the idea that "given some set of inputs, the rules determine what the output should be." [34] These rules help the system get from the problem statement to the answer by manipulating the initial data, according to the rules, to get the solution.

One specific type of rule-based system is a canonical system. These systems utilize the alphabet to make strings of information. These systems basically take the initial state, and manipulate it by rewriting it into other forms until the answer is correct. This is all done by using the rules and using logic. These canonical systems are very basic forms of rule-based systems.

As stated before, syntax is very important to knowledge representation. It is equally important to problem solving. If the syntax of a problem is slightly off, then it could result in the wrong answer or the right answer for a different problem. The computer won't know any different because it will have successfully run the expert system and retrieved the correct solution, but at the same time, it's wrong because the problem statement is incorrect.

The first step in ensuring that the syntax is correct is to verify that the vocabulary of symbols and the grammar is correct. Once these are verified, the initial state of the problem can be encoded. Once the encoding starts, great care needs to be taken in order to make sure that all the steps are completed correctly.

The systems that are so dependant on the syntax and grammar are called production systems. These production systems consist of "a rule set, a rule interpreter that decides when to apply which rules, and a working memory that holds the data, goal statements and intermediate results that make up the current state of the problem." [34] The working memory is the brains behind the system. This memory is tested at each step by the system and the rule interpreter controls which data sets are used to solve the problem. Once a certain set of rules has been picked, the working memory is updated and everything is run again with the new state of the problem.

Controlling the behavior of the interpreter is very important to expert systems. The interpreter is otherwise known as the "recognize-act cycle." [34] The first step in the cycle is to match the condition to the conclusion. Once this has occurred, the cycle moves to the second step. The second step is to place the new conclusion in the working memory and remove the old information from the working memory. There are three ways that the cycle will quit. The first is if the working memory comes across a variable with no value which would mean that there are no further possible answers. The second reason for the cycle to stop is if it completes the matching of the condition to the conclusion. Finally, the third is if the embedded stop command is reached in the program itself.

Control of the interpreter is very simple, and is most often done in the coding of the program. This programmed control is referred to as a local control regime. The local controls are typically easily changeable by the programmer in the case that errors are occurring and the program isn't running properly. There is a second type of control called the global control regimes. These global regimes are typically hard coded into the programs and this makes changes to the program very difficult.

While executing the recognize-act cycle, a program may run across information that is conflicting, meaning that there are multiple matches, causing the program to slow down. When this occurs the computer must use the rules in order to determine the proper answer. The set of rules which the computer program uses is often referred to as the conflict set. When a conflict of information comes up, a specific rule is chosen and the program is continued. "Good performance from an expert system depends on certain key properties of the control regime, such as sensitivity and stability." [34] Sensitivity of a system is how quickly the system responds to change and the stability is the similarity across the systems. Without this conflict resolution expert systems would get stuck during the program and never finish.

Two common techniques for rule based systems are forward chaining and backward chaining. Forward chaining is the typical "brute force" technique where the program starts at the beginning and searches through the entire database for possible matches. In this technique there are two steps, first the pre-selection, and then selection. In the first step, the set of rules which will be used is determined. Then the program picks a particular rule to use and proceeds with it.

Backward chaining is also a brute force technique, but it is not limited to the given database. Backward chaining is able to search its database and then search outside of it by requesting certain details that it needs to complete the program. Forward chaining is limited to the given database, and if it doesn't find a match then the process will stop without an answer. With both cases the "more precise the goal, the smaller the search tree to be checked and questions to be asked." [35]

3.5 UNCERTAINTY

Uncertainty is a major concern for expert systems. There are many ways that uncertainty can occur. In most cases, uncertainty comes from a lack of information on a particular topic. This uncertainty can cause incorrect answers or wrong assumptions. Therefore, uncertainty needs to be accounted for when writing expert systems and there are a few techniques that developers can use in order to account for this uncertainty. As much as one would like to use exact reasoning methods, those that use all the facts, it is impossible because most times all the facts are not present. So, the developers use an inexact reasoning method.

The biggest culprit to uncertainty is vagueness. Often times when collecting data from the human experts, they give information that isn't detailed enough. This is where fuzzy logic comes into play. Fuzzy logic is a fancy way of saying things like "is kind of like", or "mostly like". Fuzzy logic allows developers to program around the vagueness of experts or just the lack of information. Also, there are times when the only information collected is a range of values with no concrete value. This can be considered a type of fuzzy logic because the computer will recognize that the solution may be inside that range, but not quite sure. Fuzzy logic structures are very similar to the logic structures in that they are commutative, associative, and mutually distributive. The fuzzy logic structures are loosely based on probability rules and compositions.

A part of the advantage to allowing fuzzy logic is that we use the language in our everyday speech. This makes it easy for developers to use fuzzy logic, because it is almost second nature to them. And for the most part, all of the fuzzy logic that is used in these expert systems is a modified probability problem. Probability plays a huge part in uncertainty, and there are extensive probability theorems and equations used in determining how systems will react and how systems will solve problems. However, for purposes of this paper, fuzzy logic will be excluded because the application of expert systems to rapid tooling does not require it. At the initial stages of this research and expert system development the application of fuzzy logic is too advanced.

3.6 SUMMARY

Expert systems, in their most basic form, are human emulators. Expert systems are developed using the information collected from interviews and research. The information collected then needs to be organized in a certain manner so that the computer system can recognize the information. Once the information is organized, the developers will put together the information into some type of knowledge representation format, i.e. frames. Often times when putting the information into the program multiple types of logic programs are needed to ensure that there are no conflicts in the information. The last step is to then run the system and ensure that there are no problems and that the program runs accurately.

Expert systems depend on their ability to be more accurate and efficient than humans. If an expert system cannot do these things there is no reason to use an expert system. The most common reason why the expert system is slow in the beginning is because the information that is being used is not categorized well. This is why the knowledge representation step of the process needs to be done thoroughly and cautiously. The more time spent in this step, the more likely the system will run on the first try. In order for the system to run, it needs to be developed and then tested using case studies. The following chapters will discuss the building and testing of an expert system.

With expert systems now introduced the development of a particular system specifically applicable to the selection of rapid tooling production techniques for injection molding can be presented. This is done in Chapters 4 and 5.

4 EXPERT SYSTEM DEVELOPMENT

The purpose of rapid tooling is to reduce the time to market by decreasing the manufacturing stage of the tooling process. Each company has different needs for rapid tooling, some big and some small, but there is one common element to every company. Each company is looking for the cheapest and most effective way to produce a product. With this in mind, different rapid tooling techniques need to be compared in such a way that would make those decisions easier. In previous chapters, each of the presently known techniques was briefly compared to the others by the actual process. Each process is represented on the rapid tooling characteristics chart and a process diagram as explained in chapter 2. To further the comparison of the rapid tooling techniques two more classifications were developed: the technical attributes and the business attributes. With these new classifications, the ability to select a suitable process for an application is made much easier.

This selection process will be known as an expert system. As stated earlier, the first and most important step in the development process is knowledge representation. Each of the techniques is broken down into the following classifications: the technical attributes and the business attributes.

4.1 KNOWLEDGE REPRESENTATION

In order to properly represent the information for use in the expert system a specific representation method needed to be identified. It was decided that the best method was to identify two sets of attributes, technical and business. These two attribute sets will help differentiate between the multiple techniques.

4.1.1 Technical Attributes of Rapid Tooling Techniques

The technical attributes of rapid tooling techniques are important for appropriate selection. The technical attributes identified below were determined to be the most important ones applicable to the present study. These attributes are used to narrow down the search for the correct process for a desired product application. The important technical attributes are surface hardness, surface roughness, impact strength, tolerances; complexity of the tool, size limitation, temperature range, injection pressures, materials molded and tool materials.

4.1.1.1 Surface Hardness

The surface hardness is one of the most important attributes for an injection molding tool. Surface hardness can also be thought of as wear resistance. The softer the surface material, the fewer parts per mold can be made than with a tool with a harder surface material. Also, a harder surface means higher impact strength that the tool can withstand, allowing for a wider range of materials to be used for injection molding. Surface hardness can be measured using a number of scales such as 'Vickers', 'Rockwell Hardness', and 'Shore'. For the purpose of the expert system, however, a common measurement was needed. Therefore, Brinell hardness was selected as the standard for the present study.

4.1.1.2 Surface Roughness

The surface roughness of tooling relates to both part quality and the ease of ejection from the tool after molding The smoother the tooling surface, the more likely the part will eject without any part tears or nicks. Surface roughness is typically measured in microns, but in some cases techniques are described as having a light spark finish, these techniques were then estimated in microns so that the techniques would have similar parameters.

4.1.1.3 Impact Strength

Impact strength refers to the ability to withstand high injection pressures. A tool with higher impact strength permits a larger variety of usable molding materials. Throughout the research of each technique, it was found that most companies have not tested this attribute; however, it was still deemed important. So in order to use this attribute, the techniques were reviewed in depth and a value was given to each technique. This value was determined by looking at the injection pressures, the molding materials, and the surface hardness. The values given were high, medium to high, medium, low to medium, and low.

4.1.1.4 Achievable Tolerances

A part is designed for a certain purpose and when making a mold to make these parts, the mold needs to be an exact negative of the final part. The achievable tolerance refers to the amount that a particular dimension is allowed to vary. The lower the tolerances, the more exact the finished product; however, the tighter the tolerance, the more difficult the tool is to make. The tolerances are expressed in inches.

4.1.1.5 Complexity of the Tool

Depending on the company and the application, the tool may be very complex or very simple. In many cases, the limiting factor of a process is the complexity of the desired product, which makes complexity a very important attribute to be considered during the selection process. The complexity of the tool is described as the restrictions of the process, i.e. for Direct Metal Laser Sintering (DMLS), the complexity is defined as having a minimum wall thickness of 0.6 mm. For DMLS, this means that the process can do complex parts as long as the wall thickness is at least 0.6 mm.

4.1.1.6 Size Limitation

Size limitation refers to the largest tool that can be created using a given rapid tooling process. In some cases, the size limitations might be unknown because the process being tested has not reached a 'build-size' that it could not produce, therefore the value would be "no limitations". Size limitation is compared by the largest actual tool the process can produce.

4.1.1.7 Temperature Range of Tool

The thermal properties, namely the specific heat and the thermal conductivity, are important to the injection molding process because some materials injected into these molds might require to be heated to very high temperatures in order to melt them. However, after researching each of the techniques, the values of the specific heat and thermal conductivity were unknown and it was decided to use the possible temperature range. Furthermore, a mold that encounters these materials needs to be able to withstand these temperatures. Therefore, identifying the temperature restrictions is very important to the selection of the right rapid tooling process.

4.1.1.8 Injection Pressures

Determining the injection pressures of the tool is very important because these pressures will help determine the material used to make the tool. If the desired injection pressures are high, this would mean that the mold material needs to be a strong metal mold.

4.1.1.9 Materials

After asking the questions related to the above technical parameters, certain other follow-up questions need to be answered to narrow the remaining processes. Often times knowledge of these parameters alone can narrow down all the processes. There can be times, however, when the tool attributes need to be even more specific.

The following technical attributes are still primary attributes, but can be obtained from using the above attributes.

4.1.1.9.1 Materials Molded

Rapid tooling became popular due to its quick tool production for use with a specific molding material. This is important because if the tool can only mold parts with a certain material, the process may be disregarded if the molding material is unacceptable. Furthermore, it is also important to identify the material to be molded because it may or may not have a filler in it, such as glass, which may require a higher wear resistance in the mold. Due to the wide variety of materials used to mold parts, it is necessary to classify the materials into three categories: polymers, non-polymers, and composites.

4.1.1.9.2 Tool Materials

Tools are built using a wide variety of materials. Some techniques utilize multiple materials, while some utilize only a single material. Moreover, identifying the tooling materials is important as it will contribute to the overall cost of the end tool. Again, due to the wide variety of materials used to make the tools, it was necessary to classify the materials into three categories: polymers, non-polymers and composites.

4.1.2 Business Attributes of Rapid Tooling Techniques

Much like the technical attributes, the business attributes of rapid tooling techniques are very important for the selection of a technique. Business attributes, such as cost and lead time for example, can be the determining factor of a technique's acceptability.

4.1.2.1 Availability

When deciding upon the proper process it is important to know the availability of the technology. Each of the rapid tooling techniques are presently classified in two categories, 'commercially available' and 'under development'. For this purpose, the ranking system is taken one step further and classified into three categories. The new categories are 'commercially available', 'available while patent pending' and 'under development'.

4.1.2.2 Suppliers

Knowing the supplier for each process is important to the selection of the right process. For some processes, there are a large number of suppliers which could mean competitive prices or lead times. For some, there is only one supplier and that supplier could be geographically far away, which could increase lead time. Knowing the supplier gives insight into the lead time and potential costs of the process. The suppliers will be compared by using the following categories: more than two, one, or no suppliers.

4.1.2.3 Lead Time

The lead time parameter is often confused. Lead time in this instance is described as the time that it takes to go from the finished CAD file to the finalized tool, which in general, ranges from a couple hours to a couple months.

4.1.2.4 Applicable Quantities

When deciding upon a rapid tooling process a key question to be answered is the number of parts that are needed. Some processes are able to produce a large number of parts, while others are only able to produce a few hundred. Therefore, the comparison is based on the actual number of parts per mold.

4.1.2.5 Cost of the Tool

The whole idea of rapid tooling is to cut back on production costs by making a mold that can be redesigned quickly and at a low cost. The cost of the tool can range anywhere from $200 to $20,000; so it is necessary to know the maximum allowable cost per mold.

4.1.2.6 Process Maturity

The process maturity informs the reader if the process is technically available or if the process is available through a company. This also refers to techniques that are currently under development and whether the process is in the early stages of development or if the process needs applications to try the applicability limits of the process.

4.2 PROGRAMMING THE EXPERT SYSTEM

With the knowledge representation stage complete, the next step is to produce the program which will search through the data, matching the given parameters, and produce all the matching results. To do this, an expert system shell was needed to help with the programming. The shell which fit the needs of this research is Win-Prolog, Flex system. The most recent release came out in October of 2002 by Logic Programming Associates Ltd (LPA), London, England.

Flex is based loosely on the Prolog programming language and was made user friendly by LPA. The flex shell was designed to allow users to perform searches through the use of frames, relations and actions. It is these searching techniques which will be utilized to run the expert system as applied to Rapid Tooling. The use of relations will be the main search technique for this expert system and these relations will be supported by rules and actions throughout the execution of the program.

The most difficult part of programming an expert system is getting the proper order of execution. The first step in programming was to determine what actions needed to be performed. It was known that the attributes were classified into two categories, the technical and business attributes. The unknown, however, was how to manipulate those categories in the most efficient manner. It turns out that this unknown led to three phases of the program development, each with its own action sequence. During these three phases, the program developed progressively and became more efficient. The third and final phase led to the final efficient and effective expert system tool.

4.2.1 Phase 1 Program Development

Phase 1 was the first attempt at getting the action sequence right. The original thought was to ask all the attribute questions upfront and store all the information in variables. These variables would then be compared to the values in each of the techniques to find matches. For example, the program would ask "What is the desired lead time?" The user would select one of the options in the menu and that answer would be stored in the variable 'lead time'. Then the next question "What is the cost you are willing to spend, in US dollars?" would be asked. Again the user would select the corresponding value and it would be stored in "cost". The program would move on to the next question and would continue to do so until all the questions, both technical and business, had been asked. Once the entire list of questions had been answered then the program will move to the relations. The relations are simply the techniques and its attributes. Figure 4-1 is an example of how the relations are written in FLEX.

```
relation technique(B)
    if surface_hardness is between_220_and_375
    and impact_strength is low
    and surface_roughness is between_10_and_50_mm
    and tolerances is 'between_+/-_0.0007_and_0.002_in'
    and toolsize is no_size_limitations
    and complexity is no_limitations
    and injection_pressures is low_pressures
    and thermal_properties is low_temperatures
    and lead_time is under_2
    and suppliers is various
    and acceptable_quantities is under_500
    and relative_cost is between_4000_and_6000
    and process_maturity is readily_available
    and availability is commercially_available
    and tool_material is parameter_unknown
    and mold_material is parameter_unknown
    and B = ' RTV '.
```

Figure 4-1: Example of a relation in FLEX

The program will enter into the relation with the values of each of the questions stored as a variable. The program is looking for a true or false answer for each of the relations. A true answer will be given if while running through the relation each of the variables match those within the relation. If the relation returns a true value, the program will remember the name of that relation and continue on until it has searched all of the relevant relations. If the relation returns a false value, then the relation is forgotten and the program will move on until all the relations have values of true or false. Once the search is complete the program will output the relations that resulted in true values to the console, these relations are the techniques which matched all parameters.

When testing began, things were not looking very positive, because rarely the program would come up with matches for the entered parameters. These results required some revamping of the program. The first step at correcting the program was to allow for more answers to be accepted for each technique, meaning if the lead time desired was four to six weeks, then a lead time of two to four weeks would also be acceptable. The parameters of each technique were adjusted in hopes of obtaining better results. The results showed a small improvement in matches; however, matches were only occurring two percent of the time. More changes needed to be made.

The next attempt at correcting the problem was to add 'parameter unknown', 'parameter not important', and 'parameter varies' options to each of the attributes. This addition would allow the user to skip an attribute while not canceling it out as a possibility. The results of this addition were positive, but still not good enough. Matches were only occurring about five percent of the time. These results suggested the need for another approach.

4.2.2 Phase 2 Program Development

After trying to increase the number of matches by adding values to the parameters, and the three general parameters, it was decided that a different search method should be tried. The method was very similar to the first method; however, the major change was in the number of questions before searching the relations. The idea of actually splitting up the questions in attribute groups was done prior to writing the program to help organize the data; so why not make that the searching method?

The attributes were split up into two groups, the technical and business. Now the program has two sets of questions to ask, but this requires more actions. The two groups of questions are separated and then the technique attributes are separated creating a set of technical attributes and a set of business attributes for every technique. The program now has two distinct actions, so there must be a way to compare the results of each action. More importantly, there needs to be some way for each action to interact with the other.

In order to get the two actions to interact with one another, the idea was to use "if-then" statements to call the actions. First, the user would be asked to pick the attribute group to start with, namely, the business or technical attributes. For instance, let's say that the user chose the technical attributes. That answer would call the technical action and the questions regarding those attributes would be asked and searched. Once all the technical questions were asked the business questions would be asked and the program would then search the business relations. This idea worked perfectly until it finished asking the questions. After the searches were complete, the program would output the results in two separate lists. This result was positive such that it produced results more frequently; however, the program didn't compare the two sets of information and more importantly, there were times when one of the attribute groups resulted in no matches and printed '[ ]' to the screen. This meant that more programming needed to be done.

To get the two lists to compare one another was the easy part. Simply setting up a findall command in such a way that it took the results of the first set and then the second set of attributes and found the similar technique(s) in both and wrote those to the screen. The harder part was to anticipate the empty set. To do this the program had to be written such that if the parameters entered produced an empty set, the user would be prompted that no solutions were found and was asked to start again. These two changes increased the positive matches by 15 percent. The addition of the findall and compare command lines allowed the program to produce more frequent matches, but the percentage of positive matches was still well below the desired 50 percent.

Along with the pairing of these two attribute groups, a break point was placed between the two groups. The purpose of this break point was to allow the user to stop the program if the user was successful in narrowing down the many techniques to a manageable number that the user was satisfied with. On the other hand, if the user wanted to continue, the program would allow that, assuming that the continue option had been selected, at which point the program remembers which attribute group it started with and will run the other attribute group. The sole purpose of this addition to the program was to allow easy access to a single set of attributes if the user only wanted to use the business or the technical attributes.

Another addition to this phase was a 'read me' file. This file was designed to introduce the user to the program and to help the user understand how the program works. It is here where the user will learn which questions will be asked and how to proceed through the program. The intent was for the user to read this first and then try to run the program. By reading this document the user would be able to gather all the information that they could before the program was run. This prior research would lead to the most accurate results. Even with all these additions and changes to the first phase of the program, phase two was still not getting the needed results so more changes were needed.

4.2.3 Phase 3 Program Development

Phase three was the solution to all the problems listed above and also incorporated more modifications to make the program the most user-friendly. It is here that individual attribute groups were incorporated; the material attributes were split from the technical attributes, the process list was included, and the dialog boxes were modified to make the program user-friendly.

The first modification in phase 2 was to have a full run option as well as an individual attribute group option. To do this meant to take each of the attribute groups, business and technical, and create their own actions. Creating an action for the technical and business attributes simply meant that the user would be able to run just the technical questions or just the business questions and get the results to those parameters. This option was intended to act as a support for the full run action. The user should run the full run action and when the full run does not produce a result then the user will have the option to run the individual attribute groups to see what types of techniques the different parameters match. Having this option available to the user increases the chance for a result and provides more information to the user.

While running through the full run action using the phase 2 program, it was discovered that the material used to mold and to produce the tool were the limiting factors of the program. If those materials were removed from the question list, matches would be produced about 35 to 45 percent of the time. The material selection is an important parameter to rapid tooling so it couldn't be left out, but selecting a material was limiting the number of technique matches due to the large variety of materials. This led to the idea that the material selection should have its own action. This action would ask the user for the selection of molding material and tool building materials. This action, much like the technical and business actions, could be run as part of the full run action or an individual action.

As stated above, there is a wide variety of materials to choose from, so to secure more matches the materials were categorized into three types: polymers, non-polymers, and composites. It was thought that all the materials would fit into one of these categories thereby increasing the number of matches per material selection.

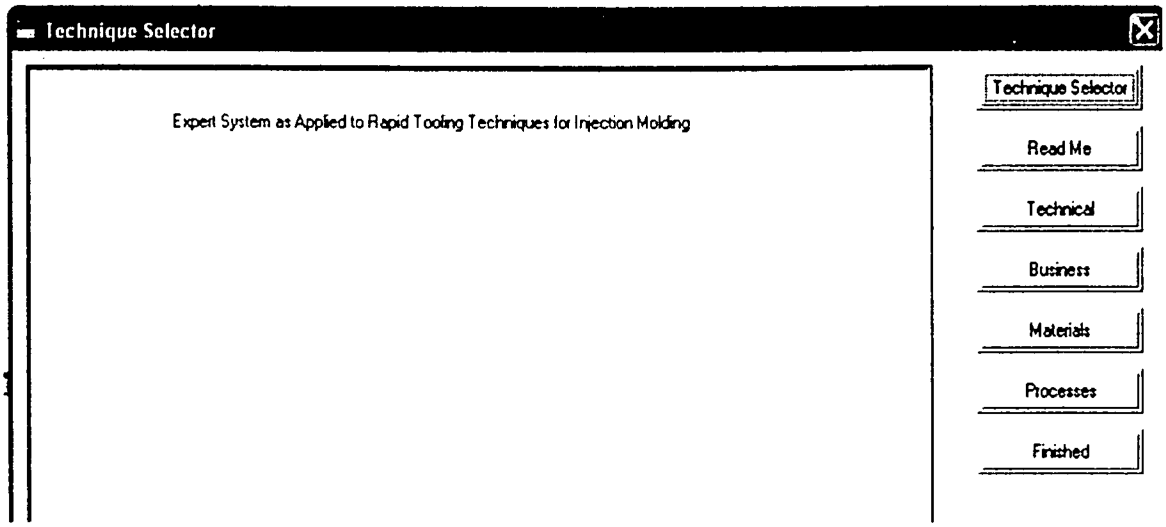
Next, a list of all the processes was added to the end of the program. This list would write the pertinent information of each technique to the console window. But the question arises, why would the user want all the techniques printed to the screen? Why not just the ones that matched the results? So a feature was added to remember the results of running the program and then a ruleset was introduced. Figure 4-2 is an example of how a section of one of the rules in a ruleset would look. The program would produce a result and store that result in the variable 'techno', and the user would be asked to either display the process information of each of the matched techniques or to select particular techniques. If the user chose to display the matched techniques then the ruleset would look through all the rules, as seen below, and determine if the technique was in the variable ‘techno’ and if it was it would execute that rule, if not it would move on. The same would happen if the user would select their own. However, in that case, the techniques selected would be stored in the variable ‘techno’, overwriting the results of the previously run program and display the selected techniques.

```
rule
   if the techno includes ' 3D Keltool '
   then technique becomes '3D Keltool'
   and lead becomes '1 - 6 weeks'
   and suppliers becomes '3D Systems and Licensees'
   and quantities becomes '50 to millions'
   and cost becomes '$2000 to $5000'
   and maturity becomes 'early stages of technical
development'
   and nl
   and write_black('The technique chosen was... ') and
write_blue(technique) and nl
   and write_black('The lead time is... ') and
write_italic(lead) and nl
   and write_black('The suppliers are... ') and
write_italic(suppliers) and nl
   and write_black('The acceptable quantities are... ') and
write_italic(quantities) and nl
   and write_black('The cost,in US dollars, is... ') and
write_italic(cost) and nl
   and write_black('The process maturity is... ') and
write_italic(maturity) and nl
and write_black('The availability is... ')
```

Figure 4-2: Example of a ruleset in FLEX

Giving the user the option to learn more about the techniques was vital, because throughout the program, the questions are answered with generalized answers. This means that each of the techniques were reviewed and each of the parameters were put into groups so that the expert system would be able to produce results. When the techniques were printed to the screen at the end of running the program, the user would be able to see the actual capabilities and limitations of each of the techniques. This would serve as a starting point for the user and the user could make a final decision based on the given information. The purpose of this expert system is not to tell the user exactly what techniques to use for a certain application. This expert system is designed to narrow down the fifty techniques into five or fewer.

The last step was to make the program user-friendly. This meant the use of buttons, explanations, and other aesthetic features. To help the user navigate through the program it was determined that the best aide would be a central console window with user interface buttons and an output window. Figure 4-3 demonstrates what the program window looks like. It can be seen that there are buttons for each of the individual attribute groups as well as a button for the complete run or "technique selector". These buttons were designed for straight forward use and were not meant to confuse the user. The idea of a button is based on the idea that not everyone knows how to talk to programming languages, so the programmer will program an action button so that the user clicks on it and the program runs. There is also a button for the "Readme" file and the processes which will output the information on each of the techniques. The last button on the screen is the finished button which will close out the program once the user is done.



Expert System as Applied to Rapid Tooling Techniques for Injection Molding

Figure 4-3: Main Program Window

Often times while running the program it was found that the questions could be somewhat confusing, especially to someone who is not particularly familiar with injection molding. To help alleviate this problem, each question was given an explanation option. Here the user would be able to get an in depth explanation of what exactly the question was asking. Often times the explanation would be a definition of the phrasing used, or an explanation of the units of the answers.

One last idea to make this a user-friendly program was to format the fonts, and display buttons. Originally when the output was written to the main window, it was in a small font and all in the same color. So the program was modified to not only help the user see the font better, but also differentiate between the technical, business, and material attributes. The formatted fonts also help differentiate the parameters from the results. The font wasn't the only thing that was modified slightly, the buttons were as well. The buttons were made so that when the user sees the buttons on the side of the main window, they are discernable as buttons and the user will know just by looking at them that they are to be pushed and something will happen.

4.3 PRELIMINARY TESTING OF THE PROGRAM

At this point in the programming it was determined that the program was running effectively enough to begin running tests and perform case studies. However, in the first test there were many errors found in the program, most of which were minor, there were a few that needed to be addressed. First and foremost, when the user would run the full program and obtain matches for the technical attributes on the first attempt, continued on to the business attributes and got no matches of the business parameters the program would freeze up and quit. Upon investigation of the problem it was found that whenever the program had no produced no results, there should be a procedure for restarting the business attributes. However, the procedure had to be worded properly because if the program calls a restart, than all values were deleted and the program became a clean slate. Clearing the variables was good for the business attributes but once the user was able to produce technique matches the technical attributes would have no values which in turn meant that there would be no matches across the two attribute groups. With that problem fixed, the program could be run again to determine other problems.

A second problem encountered was that if the user ran the program using the technique selector button, and then attempted to run one of the individual attribute groups the program would simply output the same parameters which were put into the first run. This meant that the user could not run a separate test with a new set of parameters. This simple fix was a matter of separating the full run program with the individual attribute groups and giving them their own actions.

Throughout the programming step of this expert system there were three phases or versions used to get a good program. Using the three phase approach meant that testing could occur throughout the process instead of at the end. Because testing was performed throughout the programming there were few major errors found with the program during the main testing. There were also plenty of minor errors that were found. For example, there were a few spelling and formatting errors throughout the "read me" file. A slight error in the spelling of technique names in each of the attribute groups was causing matching errors. In most cases, there were spelling or spacing differences in the variables such that when matching should occur it wasn't, for example, 'DMLS' vs. 'DMLS '. In FLEX those variables would be seen as completely different even though to the normal person they seem to be the same thing. It is these minor errors that were caught in the initial testing of the program. The real test however, will come when the case studies are run against the program.

4.4 SUMMARY

The first step in the development of the expert system was to determine exactly how the information was going to be represented. Each of the techniques was broken down into their technical and business attributes. These attributes would then serve as the search criteria. The technical attributes consisted of surface hardness, surface roughness, impact strength, tolerance capability, build size, complexity, injection pressures, thermal ranges, molding materials, and tool materials. The business attributes consisted of lead time, acceptable quantities, suppliers, maturity level, availability, and cost.

The next step was to use that knowledge and program it in such a way that a user will be asked questions and depending on the answers given, the program will narrow down the number of techniques from approximately 35 to between five and eight. The programming step was done in phases because it was assumed that errors were going to occur. So, a decision was made on how to arrange the program, it was written and then executed. Each time the program was executed at the different phases, a new issue would present itself, so the program would be reorganized and re-executed. It was in the third phase that the appropriate approach had been found. Modifications were made to make the program user-friendly and run as efficiently as possible.

Even though these types of tests can be run on the program to ensure that it is working properly with no problems, it lacks real world testing. In order to ensure that the program is running to the best of its abilities, there needs to be case studies done. These case studies will be real world applications such as a locker door handle or an electrical connector where the user would know most of the parameters. Using these case studies, it will be easier to determine where the problem areas are in the program.

5 CASE STUDIES

Out of all the methods previously described, the most effective way to test the expert system is to run "real-world" examples. These examples are useful in identifying the problem areas of the program as well as its usefulness. The goal of this expert system is for it to be applied to as many different industries as possible. With this goal in mind, case studies will be performed in multiple industries, namely, automotive and aerospace, electronics, schools, and the toy industry. After the expert system has been run using the examples below, the resulting techniques will be reviewed to determine the utility of the expert system.

5.1 AUTOMOTIVE AND AEROSPACE INDUSTRIES

The automotive and aerospace industries represent a large part of the United States' economy, so it would be important to the growth and acceptance of this expert system based tool to be useful in these industries. These two industries make very large and often complex parts. This will present a challenge for the expert system as it was originally designed for small simple parts. The purpose of testing with such larger parts is to identify the limitations of the program. There will be three examples; an engine block, an intake manifold and a turbine blade.

5.1.1 Engine Block Application

The first example to be discussed is the engine block. Figure 5-1 contains an illustration of the molded engine block using a specific molding technique called ProMetal™. The engine block was chosen due its complexity. It has cooling channels and oil lines which typically require very intricate machining techniques. It also has undercuts, slots, very tight tolerances and is typically made of metal in order to withstand the high operation temperatures, pressures and frequency flows. These issues make it the perfect candidate for testing the expert system since the molding materials are typically the limiting factors of the expert system. The engine block below was made by a ProMetal™ casting process. Knowing this information, the expert system should produce at least one match with the hope of multiple matches.

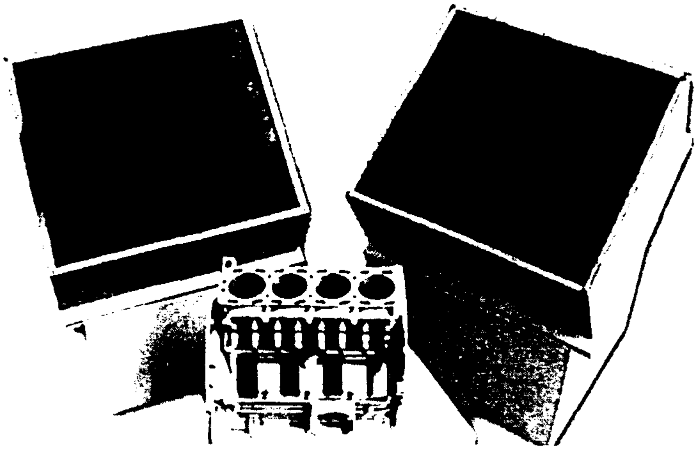


Figure 5-1: Engine Block (www.prometal.com)

In order to run the example through the expert system, the technical and business attributes needed to be identified. The easiest way to identify these values was to look at the final application of the part to be molded. Since this is an engine block, the material will need to be a metal. The selection of metal identifies high injection pressures and temperatures. That is an example of how the values listed in

Table 5-1 were identified. The attributes in the table below are separated into the technical and the business attributes to make it easier to run the program. The business attributes in this case were estimated since most of the values are unknown. Here, it is worth noting that even though there are unknown values for the business attributes, the test will perform better if the values are estimated.

Technical Technique Attributes	Value	Business Technique Attributes	Value
Surface Hardness	Between 375 and 650	Lead Time	between 2 and 4 weeks
Impact Strength	high	Suppliers	one
Surface Roughness	between 1 and 10 microns	Quantities	under 500
Tolerances	± 0.004 and 0.008 inches	Cost	between $6000 and $8000
Build Platform Size	32 x 30 x 30 inches	Maturity Level	Technically Available
Parts Complexity	complex	Availability	Commercially Available
Injection Pressures	high		
Temperature Ranges	high		
Molding Materials	Non-polymers		
Tool Materials	Non-polymers		

Table 5-1: Technical and Business Attributes for an Engine Block

5.1.2 Air Intake Manifold

The next example of an automotive application is the air intake manifold, seen in Figure 5-2. The intake manifold is slightly less complex than the aforementioned engine block; however, it is quite large. The air intake manifold will see high pressures and flows since this is the part of the automobile engine where the air and fuel combines and enters the cylinders for combustion. The intake manifold is a good test specimen because it has a variety of important features in it. A couple of these keys features are the varying tolerances and surface roughness, and different types of slots and undercuts. These attributes of the intake manifold will be used to help identify the flexibility of the expert system. This is very important because, often times, molds do not have uniform attribute values throughout, so a varying factor has to be taken into account. The intake shown in Figure 5-2 was produced by ProMetal™ in approximately five days. Knowing this information demonstrates that, again, the expert system should produce at least the one match with the hope of multiple matches.

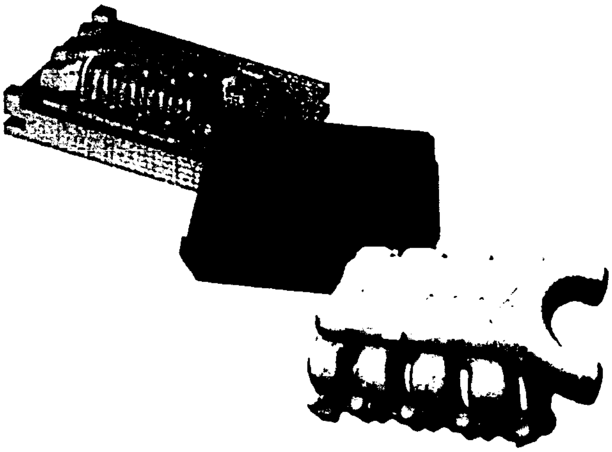


Figure 5-2: Air Intake Manifold (www.prometal.com)

Again, the testing parameters need to be identified to help run the expert system smoothly. Table 5-2 shows the values which will be used for the intake manifold. This table of values is very similar to the values chosen for the engine block. However, there is one main difference. The value for the complexity was changed from complex to moderately complex.

Technical Technique Attributes	Value
Surface Hardness	Between 375 and 650
Impact Strength	high
Surface Roughness	between 1 and 10 microns
Tolerances	± 0.004 and 0.008 inches
Build Platform Size	32 x 30 x 30 inches
Parts Complexity	moderately complex
Injection Pressures	high
Temperature Ranges	high
Molding Materials	Non-polymers
Tool Materials	Non-polymers

Business Techniques Attributes	Value
Lead Time	Under 2 weeks
Suppliers	one
Quantities	under 500
Cost	between $6000 and $8000
Maturity Level	Technically Available
Availability	Commercially Available

Table 5-2: Technical and Business Attributes for an Intake Manifold

5.1.3 Turbine Blade

The third and final example is a turbine blade for a jet engine. This is an example of a typical aerospace application and can be seen in Figure 5-3. The turbine blade looks very simple to the naked eye; however, the center of the blade is hollow, making it difficult for standard manufacturing processes. The turbine blade is typically manufactured using a casting process since an injection molded blade would not have the appropriate mechanical properties for use in a jet engine. These turbine blades need to be able to withstand very high running temperatures, as well as very high oscillations. Therefore, the material used to make these blades is typically metal. It is known that the expert system has a weakness in the processes that mold with metal but to what extent is unknown. It is important to know this weakness going into the case because once the tests are run, the exact limitation of the molding materials will be known.

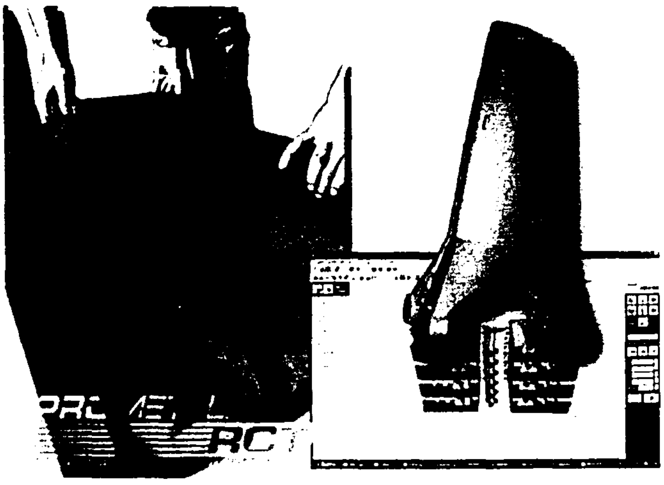


Figure 5-3: Turbine Blade for a Jet Engine (www.prometal.com)

The turbine blade represents a slightly different group of attribute values. In the case of the turbine blade, the complexity only exists in the hollow center which allows for a change in complexity from moderately complex to reasonably simple. Another difference from the two earlier examples is the change in size down to 12 x 12 x 12 inches from the larger size. All the other values listed in Table 5-3 are the same as the previous two examples.

Technical Technique Attributes	Value
Surface Hardness	Between 375 and 650
Impact Strength	high
Surface Roughness	between 1 and 10 microns
Tolerances	± 0.004 and 0.008 inches
Build Platform Size	12 x 12 x 12 inches
Parts Complexity	reasonably simple
Injection Pressures	high
Temperature Ranges	high
Molding Materials	Non-polymers
Tool Materials	Non-polymers

Business Technique Attributes	Value
Lead Time	Under 2 weeks
Suppliers	one
Quantities	under 500
Cost	between $6000 and $8000
Maturity Level	Technically Available
Availability	Commercially Available

Table 5-3: Technical and Business Attributes for the Turbine Blade

As stated previously all three of the examples above were produced by a ProMetal^{TM} process. The purpose of using an example that is known to be made using a rapid tooling technique was to determine if the expert system would produce ProMetal^{TM} as a match to the parameters given along with other techniques. The other three case studies will use examples which are not presently being produced in order to test the output of the expert system.

5.2 ELECTRONICS INDUSTRY EXAMPLES

The electronics industry was a key player motivating the development of this expert system. The electronics industry is constantly making new and redeveloped products. With each one, there is an extensive research and development process. At some point during these processes, the parts need to be produced for testing. There is one important feature that these test parts need to have: the end material. When these new products are being made, the material which will be used plays a huge role. In most cases, the product requires the material to have certain electrical conductivity or thermal properties. This is where rapid tooling becomes very important. A standard prototype can be used to test most things: fit and aesthetics, to name a few tests. The two tests that these prototypes can't be used for are the conductivity levels and thermal levels. Enter the rapid tooling mold. The rapid tooling mold made quickly and inexpensively, allows the research department to mold a few samples of the product using the actual target product material. These parts can then be tested to determine conductivity levels and the thermal properties. These parts will also show the problems with the mold. Because rapid tooling is relatively inexpensive, the mold can be redone and parts molded in the new mold without spending money on production tooling.

Figure 5-4: Various Kinds of Electronic Connectors

Aside from the materials issue, there is another important reason why the electrical industry was included as a case study class. Looking at Figure 5-4, it can be seen that these connectors are very complex. Each of these connectors has either small pins or receptors for small pins. For each of these parts, a highly complex mold has to be produced. Also, these parts are a variety of sizes, but for the most part they are small, less than two square inches. These two features, combined with the materials issue, make this a good test to identify the true limitations of the expert system.

The information for the different attributes was gathered in the same way as the engine block, intake manifold, and turbine blade. These electrical connectors don't need the surface hardness that the previous examples did, but the tolerances and platform size are significantly different. For the electrical connectors, the tolerances are ±0.004 and 0.008 inches and the platform size is the smallest allowed by the program, 5 x 5 x 3 inches. These values were determined knowing that potential materials to be molded were polycarbonates and nylons. These materials have more stringent molding parameters, so the properties that the mold requires are easy to identify. The business attributes, the lead time and cost, were given low values because those are the typical values that most research and development companies will use. Table 5-4 shows both the technical and business attributes for electrical connectors.

Technical Technique Attributes	Value
Surface Hardness	Between 110 and 145
Impact Strength	low to medium
Surface Roughness	between 10 and 50 microns
Tolerances	± 0.004 and 0.008 inches
Build Platform Size	5 x 5 x 3 inches
Parts Complexity	complex
Injection Pressures	nominal
Temperature Ranges	nominal
Molding Materials	polymers
Tool Materials	polymers / non-polymers

Business Technique Attributes	Value
Lead Time	Under 2 weeks
Suppliers	two or more
Quantities	Under 500
Cost	between $2000 and $4000
Maturity Level	Technically Available
Availability	Commercially Available

Table 5-4: Technical and Business Attributes for Electrical Connectors

5.3 SCHOOLS

Schools have lockers which have locker handles. As part of a separate ongoing study at Lehigh University an idea was devised to replace all the present locker handles with a new mechanism made out of plastic. The new handle would replace the old handle by utilizing a single sliding piece acting as the locking mechanism. The locker handle would be made of a Lexan plastic made by GE, which is known for its high strength. These locker handles are low maintenance due to the few number of working parts, and the cost is lower because the cost of plastics is much lower than that of metal.

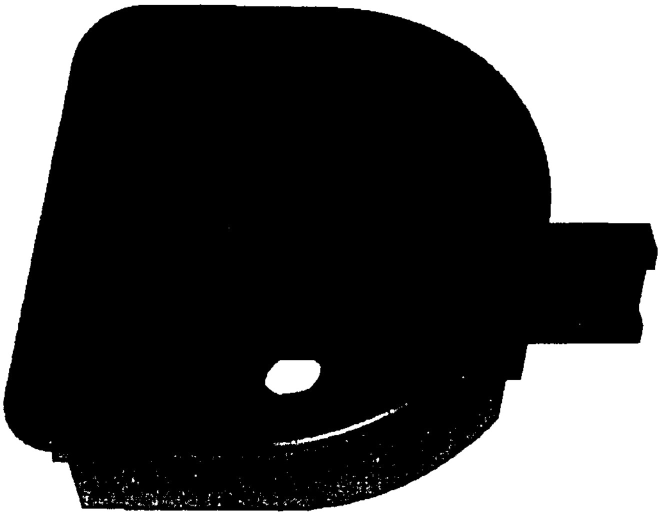


Figure 5-5: Locker Door Handle for a School Locker

This locker handle is a perfect candidate for testing this program because it is a new idea. There are no companies that are currently making this handle, so this would get this project started. The locker handle can be seen in Figure 5-5. One unique feature of this example is that the locker handle is made up of three separate pieces. The front plate is relatively simple, but is large in size. The slide bar is very simple and is not very large. The back plate has some complexity to it in the cut locations and the tolerances. On each of the three parts, the tolerances can become an issue. In general, the tolerances are ±0.005 inches, but there are some locations on all three pieces which have +0.005 and -0.0008 inches. So, a technique needs to be chosen such that it can accommodate this variety in tolerances in a single piece. An issue that arises with this application is the use of a family mold. Is there a process out there that can produce this part as a family mold, or does the part need to be produced in separate pieces? This question will have to be answered indirectly, simply because the expert system does not include family mold questions. The expert system does, however, address the build size. So, the idea of a family mold can be answered in that question, by simply using a larger build size. Upon completion of the program, when reviewing the matching processes, the user will know which company to approach to ask the specific question of a family mold for this handle.

Technical Technique Attributes	Value	Business Technique Attributes	Value
Surface Hardness	Between 220 and 375	Lead Time	Between 2 and 4 weeks
Impact Strength	medium	Suppliers	two or more
Surface Roughness	between 10 and 50 microns	Quantities	between 1000 and 10,000
Tolerances	± 0.008 and 0.01 inches	Cost	between $4000 and $6000
Build Platform Size	12 x 12 x 12 inches	Maturity Level	Technically Available
Parts Complexity	moderately complex	Availability	Commercially Available
Injection Pressures	nominal		
Temperature Ranges	nominal		
Molding Materials	polymers		
Tool Materials	Non-polymers		

Table 5-5: Technical and Business Attributes for Locker Door Handle

Identifying these parameters was a lot easier than the previous examples and most of the information was known. In Table 5-5, the technical attributes show that it is slightly similar to the two previous examples. In this case, most of the business attributes were known since this is a project that is just getting started. Speaking with the maker of this handle, the most important and critical attribute was the cost. The cost was set to between $4000 and $6000; however, anything less than that would be ideal. The lead time was also important but more flexible at between 2 and 4 weeks. For all the other examples previously discussed, the lead time and cost were known. The rest of the attributes, at least for the other examples were unknown. On the other hand, for the locker handle, the rest of the attribute values listed below are the required values. This handle will also be run with a metal as the molding material to determine the limitations of rapid tooling for this application. When the expert system is run, the hope is to be able to achieve most of these attributes, but there is some flexibility to them.

5.4 TOY INDUSTRY EXAMPLE

The toy industry would benefit greatly from a rapid tooling technique because of the low cost of production tooling for large production runs. Toy cars are probably one of the most played with toys by small children and maybe one of the most fun to design. Each toy car gets machined once and then injection molded or cast molded maybe 50,000 times. For this case study, a newly designed matchbox car will be the guinea pig. This matchbox car will be a standard design with a polished surface finish. The car is approximately 3 inches long by 1 inch wide and 1 inch high like the one seen in Figure 5-6. This small car will be perfect for testing the size limitations of the expert system, as well as point out any issues with the surface roughness.

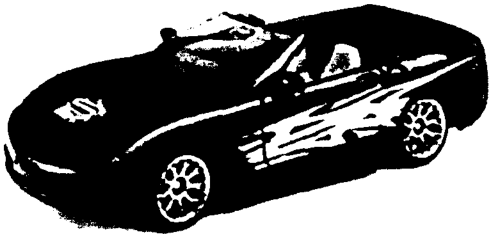


Figure 5-6: Matchbox Car (www.matchbox.com)

Matchbox cars are not typically made using the rapid tooling process, however, with the new technology this might allow toy car companies like Mattel to make these cars less expensive. Often times in designing new cars, the mold will be modified to fix problems that were not identified until after the car had been molded a couple of times, and this increases the lead time on a mold as well as the cost of the project.

These cars are a dramatic change from the automotive industry or the school industry because the shear size of the cars. Even though the main difference is the size, the complexity is little to none and the tolerances are pretty standard, although in most cases the tolerance are not very tight. The toy car, like the school example, is useful in testing the business attributes, because more of the values are known. In this case, the acceptable quantities are in the thousands and the suppliers are typically in the two or more range. As stated on the previous page, because the cost of each car needs to be low, the production costs need to be low, so this will test the cost limitations of the expert system.

Technical Technique Attributes	Value
Surface Hardness	Between 110 and 145
Impact Strength	medium
Surface Roughness	between 10 and 50 microns
Tolerances	± 0.01 and 0.04 inches
Build Platform Size	5 x 5 x 3 inches
Parts Complexity	reasonably simple
Injection Pressures	nominal
Temperature Ranges	nominal
Molding Materials	Non-polymers
Tool Materials	polymers

Business Technique Attributes	Value
Lead Time	Under 2 weeks
Suppliers	two or more
Quantities	between 1000 and 10,000
Cost	between $4000 and $6000
Maturity Level	Technically Available
Availability	Commercially Available

Table 5-6: Technical and Business Attributes for Matchbox Car

Through the use of these case studies, it is hoped to discover the programming limitations of the developed expert system. Each case study was chosen in order to focus on a particular part of the expert system. The automotive and aerospace examples were chosen because of their large sizes and complexity. The electronics industry focuses on the actual molding material limitations. The locker handle is testing the expert system as a whole because the locker handle assembly has three different sized parts, some complexity, varying tolerances, and allows for a variety of materials for molding. And the last industry, the toy industry, focuses the expert system on very small applications testing the small and detail limitations of the expert system.

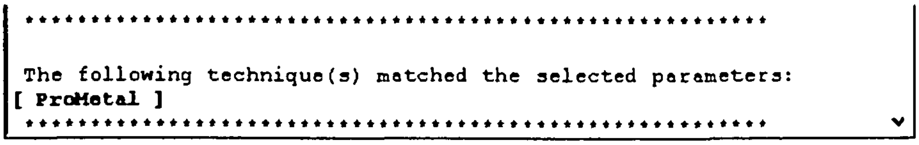
6 RESULTS AND DISCUSSION

With the case studies identified, it is possible to start running the program and test for its limitations. Each one of the examples was run using the identified parameters from chapter 5. In some cases, the initial parameters were modified to determine the programs limitations. Even though the case studies were chosen for specific purposes, there were occasions when other limitations were found. All case studies were run once before any modifications were made to the parameters to determine the limitations.

6.1 AUTOMOTIVE AND AEROSPACE INDUSTRY EXAMPLES

6.1.1 Engine Block Results

The first test was run on the engine block. Using the identified parameters in section 5.1, the program produced a match of one technique, ProMetal^{TM}. This was the anticipated result, especially since the engine block used as the example was produced by ProMetal^{TM}. This is a good result in the fact that the program is working properly to produce the right technique for this application. However, the hope was to be able to obtain more than one result for the engine block. Figure 6-1 is a screen shot of the output from the expert system for the engine block.



```
 *********************************************************

 The following technique(s) matched the selected parameters:
[ ProMetal ]
 *********************************************************
```

Figure 6-1: A Portion of the Output of Engine Block example

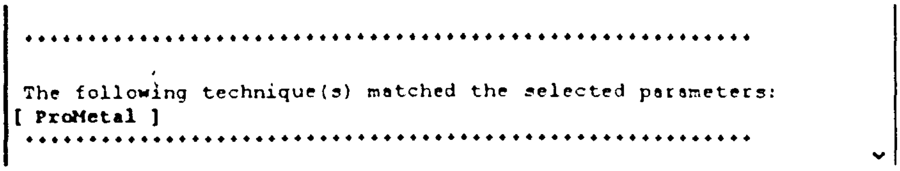
Breaking down the program, it is found that the initial parameters for the technical attributes produced two processes, PolySteel™ and ProMetal™. The business attributes produced all techniques, which points the limitations to the technical attributes. In order to identify the limiting factor for the engine block, the parameters were changed one at a time to determine the result. In Table 6-1, the initial values are compared to the new values, which produced more techniques. With this example, however, the modified values only produced at total of 3 techniques: 3D Printing, PolySteel™, and ProMetal™. The values can not be changed any further due to the minimum required values for the engine block. The changes can be seen in the surface hardness, impact strength and surface roughness, but the other parameters remained unchanged because they were not flexible enough to change the value. The other changes were a little more flexible, but each of the parameters was lowered by one option because any further and the parameter would be less than the required minimum. The engine block example points out that there are a limited number of techniques with the necessary capabilities to produce such a complex and high pressure and temperature range part.

Technical Technique Attributes	Initial Value	New Values
Surface Hardness	Between 375 and 650	between 220 and 375
Impact Strength	high	medium to high
Surface Roughness	between 1 and 10 microns	between 10 and 50 microns
Tolerances	± 0.004 and 0.008 inches	± 0.004 and 0.008 inches
Build Platform Size	32 x 30 x 30 inches	32 x 30 x 30 inches
Parts Complexity	complex	complex
Injection Pressures	high	high
Temperature Ranges	high	high
Molding Materials	Non-polymers	Non-polymers
Tool Materials	Non-polymers	Non-polymers

Table 6-1: New Parameter Values to increase Program output

6.1.2 Air Intake Manifold Results

The next example was the air intake manifold. Running the program using the initial parameter values, the program produced the same result as the engine block example, ProMetal™. This was the anticipated result for this example because it was an example produced by the ProMetal™ technique. This again demonstrates that the program is running properly, however, it begs the question, is this expert system capable of handling larger scale parts? It seems that there are a very limited number of techniques which can produce the larger parts.



```
 **************************************************

 The following technique(s) matched the selected parameters:
[ ProMetal ]
 **************************************************
```

Figure 6-2: A Portion of the Output of Intake Manifold example

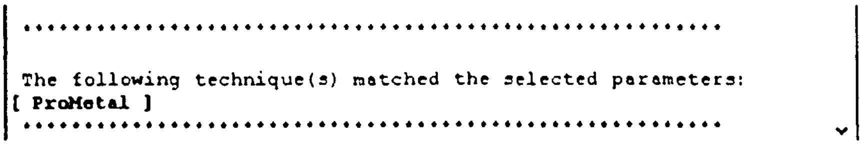
Further tests were run on the intake manifold by modifying some of the parameters to possibly get better results from the expert system. Table 6-2 compares the initial values of the technical parameters to the new technical parameter values. The reason that the technical attributes have been used to get better results was because the business attributes already produced all the techniques, while the technical attributes only produced one technique, ProMetal^{TM}. In an attempt to get better results, the surface hardness, impact strength, surface roughness, and tolerances were adjusted by one value. The air intake manifold, unlike the engine block, has more flexible parameter values. Because of this, the new values produced an increase in matches from one technique to nine. The increase in results was due to a combination in changes. The parameters which affected the results the most were the injection pressures and temperatures. When those two parameters were changed, the number of techniques increased to six techniques. The addition of the other changes increased the results to nine techniques.

Technical Technique Attributes	Value	New Values
Surface Hardness	Between 375 and 650	Between 220 and 375
Impact Strength	high	medium to high
Surface Roughness	between 1 and 10 microns	between 10 and 50 microns
Tolerances	± 0.004 and 0.008 inches	± 0.008 and 0.01 inches
Build Platform Size	32 x 30 x 30 inches	32 x 30 x 30 inches
Parts Complexity	moderately complex	moderately complex
Injection Pressures	high	nominal
Temperature Ranges	high	nominal
Molding Materials	Non-polymers	Non-polymers
Tool Materials	Non-polymers	Non-polymers

Table 6-2: New Parameter values for Air Intake Manifold

6.1.3 Turbine Blade Results

The final example of the automotive and aerospace industry, the turbine blade, anticipated better results due to the lower complexity of the part and the smaller size. The result was very similar to the two previous examples and only produced one, ProMetal™ as seen in Figure 6-3. Again, this was the anticipated result, but the lack of more techniques is disappointing. After running the first two examples, it was thought that a smaller size and lower complexity would produce more matches. It was demonstrated, however, that the limiting factors with these examples are the injection pressures and temperature ranges. To increase the number of matches, the first modifications in the parameter values are the temperature ranges and injection pressures.



```
 ********************************************************

 The following technique(s) matched the selected parameters:
[ ProMetal ]
 ********************************************************
```

Figure 6-3: A Portion of the Output of Turbine Blade example

Changing both the temperature range and the injection pressures increased the number of techniques to five techniques. This change identifies the major limiting factors for the automotive and aerospace industry to be the temperature ranges and injection pressures. This makes sense because the larger the part to be molded, the harder it is to maintain a high injection pressure because the outer sections of the mold will lose pressure as the mold fills. The same idea happens with the temperature where the temperature of the mold will decrease as the mold is filling, unless the thermal properties are good enough to maintain high temperatures.

Technical Technique Attributes	Value	New Values
Surface Hardness	Between 375 and 650	Between 375 and 650
Impact Strength	high	high
Surface Roughness	between 1 and 10 microns	between 1 and 10 microns
Tolerances	± 0.004 and 0.008 inches	± 0.004 and 0.008 inches
Build Platform Size	12 x 12 x 12 inches	12 x 12 x 12 inches
Parts Complexity	reasonably simple	reasonably simple
Injection Pressures	high	nominal
Temperature Ranges	high	nominal
Molding Materials	Non-polymers	Non-polymers
Tool Materials	Non-polymers	Non-polymers

Table 6-3: New Parameter values for Turbine Blade example

The other parameters were not changed with this example because once the limiting factors were identified; there was no need to continue changing the parameters. There were changes made to the other properties, but there was no significant change in the results so as stated above, the parameters were not changed in Table 6-3.

```
The techniques which matched your selected parameters where: [ProMetal]

 Below are the techniques in further detail.

The technique chosen was... ProMetal
The lead time is... 1 week
The supplier is... Extrude Hone, ProMetal Div.
The acceptable quantities are... > 10 aluminum forging,  <1000 aluminum die casting ,
> 100,000 PIM
The cost, in US dollars, is... Depends on size of part / tool
The process maturity is... technically available
The availability is... commercially available with purchase of necessary equipment
also in-house work done
The surface hardness is... Rc 26 to 30
The impact strength is... medium or high depending on molding material
The surface roughness is... 6.4 to 10.2 microns
The tolerance capabilities are... 0.005 in. + 0.002 in/in
The tool size limitations are... 40 x 20 x 10
The complexity limitations are... can have sections as thin as 1.25 mm, high strength
for handling
The injection pressure is... good range of injection pressures allowable
The temperature range is... good range of thermal properties allowable
The materials which can be molded in these tools are... thermoplastics
The materials used to produce the tools are... stainless steel and bronze; Inconel,
aluminum or gold
```

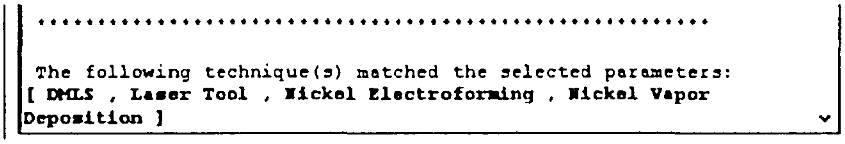
Figure 6-4: Output of the Process ProMetal™ in detail

The technique matches are not the only results that were reviewed in this process. Once the program was finished being run and the matches were identified, the actual techniques were reviewed. The expert system has an option to output each of the techniques in more detail to the main console. Figure 6-4 demonstrates what the user sees when this option is chosen. The purpose of this option is to help understand exactly what each technique can do since the expert system groups techniques into general categories. This information needs to be reviewed to ensure that the program is choosing the right techniques for the attribute parameters being input. After reviewing the information for each of the techniques which matched the initial parameter values, the program was selecting the right techniques. After the parameters were adjusted to improve the results, the techniques were reviewed to ensure that the parameters that were chosen were within the limits of each of the techniques.

When all the tests were run and analyzed, it was determined the there are some issues that need to be worked out with the expert system in order to allow the automotive and aerospace industry to utilize it. The major limitations are in the temperature ranges and the injection pressures. These two attributes, at least in the examples above, required high injection pressures and temperatures, and this would limit the number of techniques to two right away. The other attributes which were significant factors, but not major, were the size and complexity. It seems that the expert system will be more beneficial for smaller and less complex parts, than the larger parts. There are further advancements that need to be made in rapid tooling technology in order for a potential future version of this expert system to be very useful to the automotive and aerospace industry.

6.2 ELECTRONICS INDUSTRY

A high number of matches was expected for the electrical connectors example. Initially, however, the expert system produced no matches for the parameters given. The lack of matches is a huge concern, since this system was designed with the electronics industry specifically in mind. The initial parameters had a value of complex for the complexity level and it was determined that this attribute was the limiting factor for this case. The most important parameter for the electrical connectors is the complexity. The electrical connectors are complex parts because of the undercuts and slots that these parts have, so the program needed to be reviewed to ensure that there were absolutely no matches to these parameter values. Most of the techniques can handle these small sizes with tight tolerances and low impact strength, but the difficulty comes from the complexity level. So, further review of the program identified that the problem was that the complexity level was mislabeled and the associated undercuts and slots were in the moderately complex part range. This discovery led to an increase in the number of matches to five, as shown in Figure 6-5.



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 The following technique(s) matched the selected parameters:
[ DMLS , Laser Tool , Nickel Electroforming , Nickel Vapor
Deposition ]
```

Figure 6-5: A Portion of the Output of Electrical Connectors example

The modifications can be seen in Table 6-4. As stated above, the complexity was changed from complex to moderately complex. This change was needed after identifying the incorrect labeling of the undercuts and slot complexity of the electrical connectors. Due to the result of these values being a suitable number, there were no further changes made to the attributes. Another reason there were no adjustments made is because the electrical connector's attribute parameters are fixed.

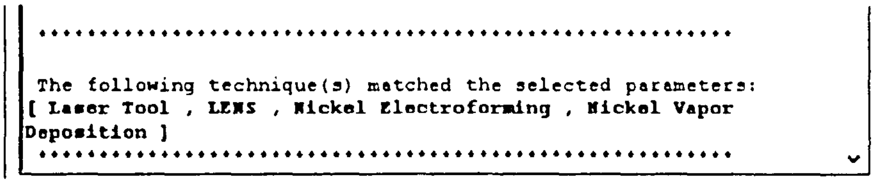
Technical Technique Attributes	Value	New Values
Surface Hardness	Between 110 and 145	Between 110 and 145
Impact Strength	low to medium	low to medium
Surface Roughness	between 10 and 50 microns	between 10 and 50 microns
Tolerances	± 0.004 and 0.008 inches	± 0.004 and 0.008 inches
Build Platform Size	5 x 5 x 3 inches	5 x 5 x 3 inches
Parts Complexity	complex	moderately complex
Injection Pressures	nominal	nominal
Temperature Ranges	nominal	nominal
Molding Materials	polymers	polymers
Tool Materials	polymers and non-polymers	polymers and non-polymers

Table 6-4: New Parameter values for Electrical Connectors example

After the matches were identified, each technique was reviewed in further detail. The techniques were reviewed and it was determined that each of the techniques would be able to produce the electrical connectors in the material needed with high accuracy. An example of what this output looks like can be seen in Figure 6-5. These results were different from the automotive and aerospace industry in the techniques which were matched. This is a good result in that it shows that the program is matching the right techniques to the parameters, but it also shows that there is a variety of applications to the expert system. The major difference in the two industries is the size and it is becoming clear that this expert system is more geared towards the smaller size and less complex parts. The next couple of tests will help identify the remaining limits to the program, however it seems that the most influential attributes have been identified, the complexity, the injection pressures, and the temperature ranges.

6.3 SCHOOL LOCKER RESULTS

The schools example, the locker handle, was unique to the list of case studies because it was an original idea being used to help get a new project off the ground. This is the typical application anticipated for the expert system. The locker handle has a very flexible set of attribute values because there is no set molding and tooling materials, the tolerances are not vital, and it is a medium sized part. The flexibility of the attribute values is helpful because it allows the expert system to find the best matches. Running the program with the initial parameters set in section 5.3 produced four matches: Laser Tool, LENS, Nickel Electroforming, and Nickel Vapor Deposition and can be seen in the screenshot, Figure 6-6.



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 The following technique(s) matched the selected parameters:
[ Laser Tool , LENS , Nickel Electroforming , Nickel Vapor
Deposition ]
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Figure 6-6: A Portion of the Output of Locker Handle example

Upon reviewing the matching results in further detail, a few of the techniques were good; however, there were two that didn't seem to be applicable. Nickel Electroforming and Nickel Vapor Deposition might be applicable to the locker handle, but there are a few parameters that are unknown at this time. This information stimulated a further review of the rest of the techniques available. Table 6-5 compares the initial values and the new modified values for the parameters used in the locker handle example. In this case, the table has both the technical and the business attributes listed below. Changing just the technical attributes was simply not enough to get better and more accurate results, so the addition of the business attributes were added. There were only a few changes made. The technical attribute, surface hardness, was changed to a lower value because it was determined that the molding material didn't require high impact strength. The business attributes saw more changes because there was more flexibility. The lead time was increased since this is a new product, but it can not be too long, because it needs to beat any competitors to the market. The number of suppliers was changed because the number of suppliers is not important to this example and the sponsor is willing to work with anyone that is willing to give a good cost. And, the last change was the increase in the cost.

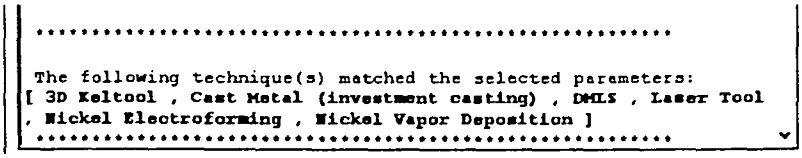
These changes produced much better results in two ways. First, the number of results increased from four to nine. Even though the two nickel processes are still in the mix, there are plenty of other viable techniques which can be used for production. And second, the actual quality of the matches was much better. Reviewing the techniques in detail revealed that the matched techniques were better suited for producing this reasonably simple, medium sized, locker handle. A question raised in section 5.3 about family molding can be answered at this point. The companies of the resulting techniques have said that a family mold is possible as long as the build size of the process is big enough. The only requirement is that the model file has to be set up as a family mold.

Technical Technique Attributes	**Value**	**New Values**
Surface Hardness	Between 220 and 375	Between 145 and 220
Impact Strength	medium	medium
Surface Roughness	between 10 and 50 microns	between 10 and 50 microns
Tolerances	± 0.008 and 0.01 inches	± 0.008 and 0.01 inches
Build Platform Size	12 x 12 x 12 inches	12 x 12 x 12 inches
Parts Complexity	moderately complex	moderately complex
Injection Pressures	nominal	nominal
Temperature Ranges	nominal	nominal
Molding Materials	polymers	polymers
Tool Materials	Non-polymers	Non-polymers
Business Technique Attributes	**Value**	**New Values**
Lead Time	Between 2 and 4 weeks	Between 4 and 6 weeks
Suppliers	two or more	not important
Quantities	between 1000 and 10,000	between 1000 and 10,000
Cost	Between $4000 and $6000	between $6000 and $8000
Maturity Level	Technically Available	Technically Available
Availability	Commercially Available	Commercially Available

Table 6-5: New Parameter values for Locker Handle example

6.4 TOY INDUSTRY RESULTS

The final case study, the toy car, produced the results that were anticipated for most of the examples. When all the other case studies were chosen, the hope was to obtain a large number of matches. However, as previously discussed, that was not the case. The toy car did just the opposite. When the initial parameters were input into the program, there were a significant number of matching techniques, six to be exact. Of these techniques, the Nickel Electroforming and Nickel Vapor Deposition were once again output. As stated in the previous section, these two techniques are questionable since a handful of the process' attributes are still unknown. More tests were run to get better results and Figure 6-7 shows those results.



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The following technique(s) matched the selected parameters:
[ 3D Keltool , Cast Metal (investment casting) , DMLS , Laser Tool
, Nickel Electroforming , Nickel Vapor Deposition ]
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Figure 6-7: A Portion of the Output of Toy Car example

After a rather significant number of tests were run, it came down to the business attributes to improve the number and quality of the results. This is another case where the business attributes are quite flexible, allowing for more variance in the values. The first change was in the number of suppliers to a value of not important. The reason for choosing the value of not important was because it does not matter to the company or companies who produce these car molds, it is a matter of cost. The next change was the number of parts per mold. It was thought that the toy industry would be able to produce their toy cars by using rapid tooling molds allowing costs to be reduced. Therefore, the number of parts was increased to 10,000 and 100,000 parts per mold. These changes, as seen in Table 6-6, produced a large increase in the number of matching techniques. The number changed from 6 to 14 techniques.

Business Technique Attributes	Value	New Values
Lead Time	Under 2 weeks	Under 2 weeks
Suppliers	two or more	not important
Quantities	between 1000 and 10,000	between 10,000 and 100,000
Cost	between $4000 and $6000	between $4000 and $6000
Maturity Level	Technically Available	Technically Available
Availability	Commercially Available	Commercially Available

Table 6-6: New Parameter values for Toy Car example

This example shows that the more simple the part, the easier it is to obtain a good number of matches. This example also illustrates that the business attributes can become more important to the simpler parts because there is more variance in the business attributes than the technical attributes.

6.5 SUMMARY

Looking at all the different case studies, it is obvious why each of the examples were chosen. The automotive and aerospace examples demonstrated that the expert system has issues dealing with large complex parts, while the toy example showed the ease of small simple parts. The toy example and the locker handle example demonstrated that even though the technical attributes can be important to the engineer and the business attributes are important to the company, the limiting factor can be a business attribute. This demonstrates the equality of importance of each attribute group. The electrical connectors demonstrated that the small complex parts have some difficulties. When running the expert system for a small complex part, each of the attributes has been looked at very closely. The more flexible that the part, the better the results.

Aside from the program actually producing matching techniques, the program has the ability to print the technique's attributes to the main console. This is important because it allows the user to identify the actual capabilities of the process. Reviewing these values will help the user cancel out a recommended technique if the values do not quite fit their needs. As seen in the locker handle example, Nickel Electroforming and Nickel Vapor Deposition were eliminated from the list of techniques due to the lack of information.

Looking back at all the results and corrections made, the program ran the way that it was supposed to and gave the right information when needed. The expert system has proven itself as a versatile program by testing its capabilities in the automotive and aerospace industry, the electronics industry, schools and the toy industry.

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSION

Due to the increasing number of rapid tooling techniques available, there needed to be a common method of comparison between techniques. The first and most important result of this study was the development of the technical and business attributes of rapid tooling techniques. Identifying these two attribute groups allowed each of the techniques to be broken down and compared on a more common level. It also helped to understand the true capabilities of each technique. However, in some cases, the information for certain attributes was difficult to obtain from the companies or universities responsible for each technique. In these cases, educated guesses were made based on the other information that was obtained from the companies, universities and general knowledge of the techniques. Without these attributes identified, the development of the expert system would have been more difficult and it was these attribute groups which became the knowledge representation format for the expert system.

This expert system asks the user questions regarding the technical and business attributes and produces a set of techniques which match the user's input. The purpose of this expert system is to get the user started with technique selection. The process also provides the user with a more in-depth description of each of the techniques' true capabilities. This in depth information is useful because the expert system required a generalization of information. This meant that in order to increase the number of matched techniques per set of parameter input the information of each technique had to be generalized into four or five options for each attribute question. In order for the user to make the right decision, the user will have to do further research on each of the techniques starting with the information given through the expert system.

After reviewing the results, the success of the expert system demonstrates that it produces results which necessitate a few minor modifications. These changes helped the program produce more results more frequently than had originally been anticipated. The initial output of the program produced one match for a specific application. Even though it produced one technique, it was thought that a single solution was not enough. It was originally thought that there should be between five and ten techniques produced from the expert system because it would allow the user to decide upon the right technique after doing some research. The expert system was to be a recommendation, not a solution. So when one process was matched in the initial run, modifications were made to increase the number of techniques. There were problems getting the number of results to be consistently between five and ten without losing the accuracy of the program. So the number of accepted matches was reduced to between two and five matches per parameter set. These results would allow the user to have options and to compare each of them in a more detailed manner, following further research of each technique.

Even with all the successful matches, there were a couple limitations that were identified. The first and most restrictive limitation was the injection pressures. When running the program, it was found that a large and complex part would not match any techniques if the injection pressures were high. This is assumed to be a problem not with the expert system but with the rapid tooling techniques that are currently available. Another restrictive limitation was the molding and tooling materials. These two attributes were restrictive due to the variety of materials. So, it was concluded that by changing the values from actual materials to polymers, non-polymers and composites, the material attributes would be more flexible. This change increased the number of matches significantly. It was changes like this that helped produce the best results from the expert system.

The expert system has several convenient characteristics which give the user a couple of options while running the program. The first option is for the user to run a full analysis which allows the user to run through all the attributes, both business and technical, and a result that matches both sets of attributes will be output. A second option allows the user to run an analysis of just the technical attributes, business attributes or the materials and a result which matches the individual attribute set will be output. The purpose of the second option is to allow the user to select just one set of attributes instead of running an entire analysis. For example, if an engineer is trying to get an idea of which techniques will work for a given set of technical attributes but does not care about the business attributes he or she would select the technical attributes program. Selecting the technical attributes program would produce a result much quicker based purely on the technical attributes. This option would also produce, on average, more techniques than selecting the full run option.

The last option allows the user to see each of the techniques in detail. Choosing this option prints the selected technique(s) and its capabilities for each attribute to the screen. This gives the user a full understanding of the limitations of each technique before starting to research the technique(s) that are adequate for a given application.

Now that companies have the knowledge of what exactly rapid tooling can do for them, and they have the software package to get started, significant amounts of money and time can be saved. The case studies proved that this program can be used to identify a technique for the large and complex parts, the large and simple parts, and so on. The versatility of the expert system will allow it to be used in almost any industry where product development plays a key role.

7.2 DIRECTIONS FOR FUTURE WORK

The program that was developed still has many kinks to work out, and further modifications in the future would render it more useful. The first step would be to perform another review of all rapid tooling techniques currently available. At the beginning of this study there were approximately 30 different techniques available and at the time of this report there are approximately 45 different techniques available. That is an addition of 15 techniques in two years, so it is important to update all the technique information. This is a two part task. First and most importantly, it is necessary to review all the techniques which were discussed in this study and update all the information. Secondly, identify and incorporate the new techniques whether under development or currently available.

Updating the information is very important because at the time of this study, there was information that was unclear or unavailable. Figure 7-1 illustrates the level of confidence vs. the level of importance of each business attribute. It can be seen in this figure that the number of suppliers is moderately important and has a low confidence level, while the acceptable quantities has a moderate importance level and a high confidence level. The goal is to get all of the business attributes into the oval at the top which would signify that all the business have an appropriate level of confidence based on parameter importance. This confidence level refers to the level of confidence in the values entered into the expert system.

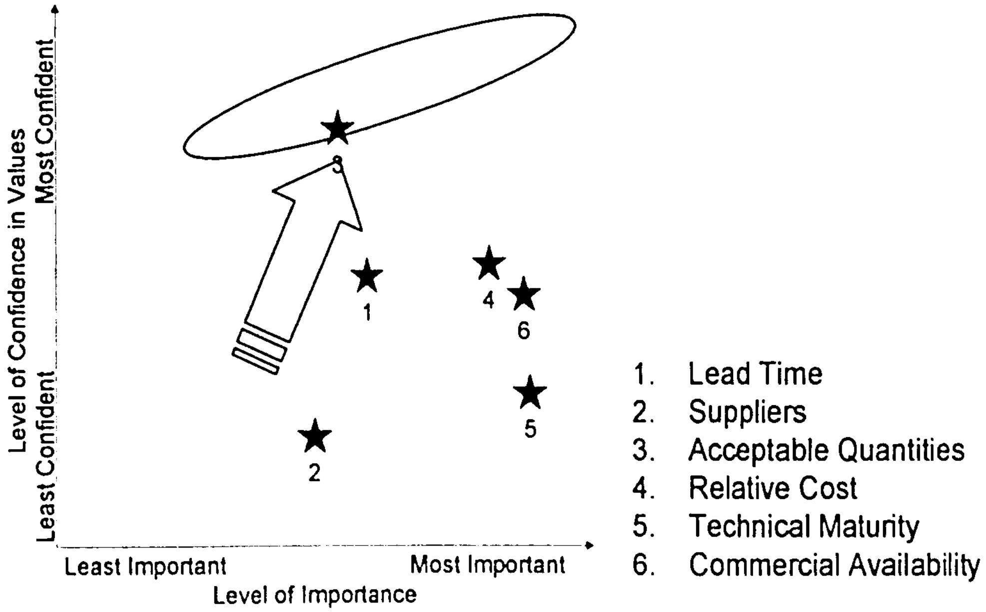

Figure 7-1: Confidence vs. Importance for Business Attributes

The technical attributes are also in need of review and updating. The idea is the same in that the goal is to get all of the technical attributes into the oval at the top of Figure 7-2, which would mean that all the values have an appropriate confidence level based on their importance. It can be seen that currently there is only one attribute, tool size, which is in the oval and it is good because it has a high importance level and high confidence level.

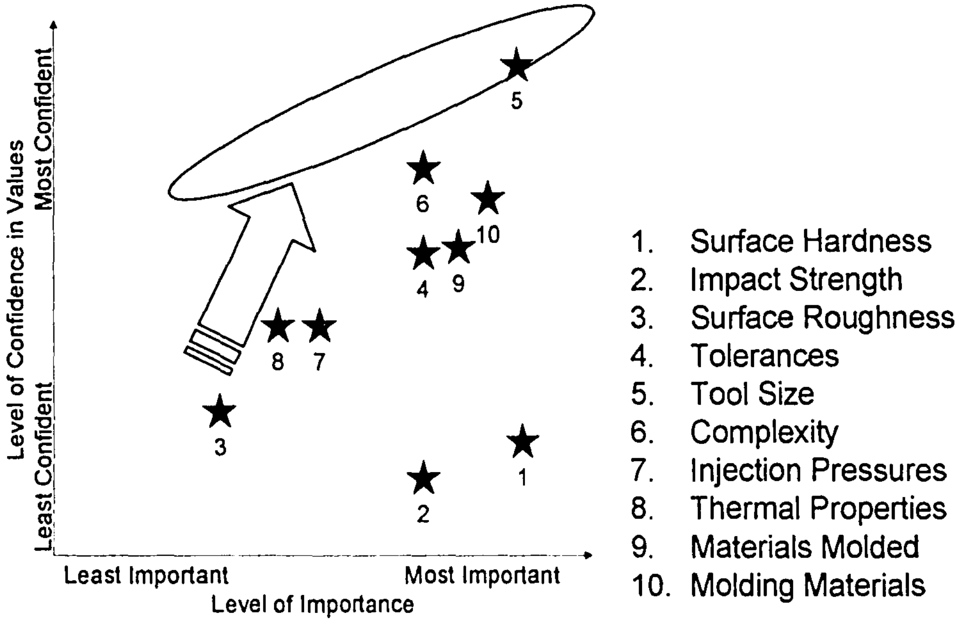

Figure 7-2: Confidence vs. Importance for Technical Attributes

These two figures are used to illustrate the fact that few of the technique attributes have a high confidence level, and this is mostly because the information from the companies is very vague or unknown. Looking again at Figure 7-2, it can be seen that the surface hardness and impact strength are of very high importance but low confidence, which should be the first priority when updating the information. And, as previously stated, this information needs to be constantly updated since there are new techniques or variations of current techniques becoming available all the time.

The second step in updating the techniques is to identify any new techniques that are being researched, released, or have become currently available. The best way to do this is to perform a literature review. This review needs to be an in-depth research of all literature and internet searches. Close attention needs to be paid to techniques which are similar because, in some cases, the new techniques are simply variations of existing methods. In these cases, a decision needs to be made as to identify each of the techniques individually or group them together and simply add the company or university to the supplier list.

Along with updating each of the techniques and adding the new ones, the attribute groups should be reviewed and modified as more techniques become available. In some cases, some attributes may become unnecessary or more important. There may be a need for more attributes to help clarify techniques as more companies are developing variations of the existing techniques.

A useful tool to help organize each of the techniques is the development of a webpage. It would be the first line of information about each of the techniques. They would be listed on the webpage with a link attaching each technique with either the company or companies responsible for the technique. The website would also explain the history behind rapid tooling, as well as a link to download the expert system software. A history and explanation of expert systems would be available to help the user understand how the software works as well as examples.

The program used for developing the expert system was Win-Prolog, by Logic Programming Associates, Ltd. The program has a lot of limitations in its capabilities and help files. The reason for using this software package was because it is an expert system shell which works well in database searches and running expert systems, so it was thought that this was a perfect match for the rapid tooling expert system. It is now thought that further research needs to go into finding the best program for the rapid tooling expert system. The result may be that the Win-Prolog software is the best option; however, there may be an alternative out there that would work better for this purpose. If this is the case, that software should be purchased and utilized making the expert system as proficient as possible. Once the best software package has been identified and purchased, if needed, then the programming of the actual expert system needs to be reviewed.

Programming this expert system was done by a mechanical engineering student with limited computer programming experience. To increase the effectiveness and the efficiency of this program, someone with more programming knowledge should be consulted. The program is still in its prototype stages, so better programming can be used and the program could be modified in such a way to allow the computer run it quicker. Along the lines of programming, the expert system currently does not have the ability to print the output. This ability has been identified as an important feature especially since there are some cases where there is a lot of information that is printed to the output console. It would make things a lot easier if the program would be able to print the output to a word document or even just a printer. Once these things have been addressed, this expert system could be utilized by people looking to produce a new product and have a limited budget, or even the big corporations to save a little money.

Some of the companies which have developed these rapid tooling techniques sell their technology to allow the buyer to produce the molds themselves. It would be a good idea to purchase some of these pieces of equipment and begin running tests on them to identify if there are any ways to improve upon their technology. It might be possible to increase the quality of the process, or even develop a new technique. Performing these tests would also help with the understanding rapid tooling.

The primary objective of the proposed research study was to identify a means by which to compare these rapid tooling techniques currently available. This study began with identifying all of the rapid tooling techniques, in different stages of availability and comparing them to one another. This comparison provided the knowledge representation for use in the expert system. This expert system asks the user questions based on the attributes and produces results which match all the selected parameters. This study identified the limitations of the expert system and ways to correct them.

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Technique Name	Surface Hardness	Impact Strength	Surface Roughness	Materials Molded	Tolerances	Tool Size Limitations	Complexity	Injection Pressures	Acceptable Quantities	Tool Materials	Thermal Properties
SI 1. RTV Molding	Shore D 72 - 82	Low	10 to 50 mm	One or Two part liquid urethane	± 0.005 in. for first inch, ± 0.002 in. for every inch after	n/a	can include undercuts and slight negative draft	Protocem uses a process where the molds don't see injection pressures because the molds are gravity filled	10 to 50	Rubber Silicone, urethanes	low thermal properties
SI 2. Aluminum-Filled Epoxy Molding	Shore D 80 - 86	Low to Medium	high finish possible, dependant on pattern	Thermoplastics	+/- 0.002 in	n/a	n/a	low relative strength = low injection pressures	Complex part: 100s Simple part: 1000s	Aluminum Filled Epoxy	315 °C
SI 3. RMT (SwifTool)	9.5 Vickers	Low to Medium depending on the molding material	light spark	thermoplastics, rubbers, ceramics planned	0.1 mm	28 x 24 x 8 in.	use steel inserts for high aspect ratio or unsupported features	same as normal injection moldings	10 to 50,000	proprietary composite materials	same as normal injection moldings
HI 1. Cast Metal (Sand)	Rc 48	Medium	60 to 90 mm	thermoplastics	± 0.003 in	30 x 30 x 12 in	no geometric limitations	same as normal injection moldings	500 - 1000s	Kirksite (zinc - aluminum alloy)	same as normal injection moldings
HI 2. Cast Metal (Rubber)	TBD	Low	TBD	thermoplastics	TBD	TBD	moderate complexity available	not intended for injection molding	TBD	Plaster	not intended for injection molding
HI 3. Cast Metal (Spin Casting)	120 bhn	Medium to High	TBD	QUICK-SETTING LIQUID THERMOSETS	± 0.005-.008 in/in.	12 x 8 x 3.5	moderate complexity available	not intended for injection molding	1000-1200 components per hour	ZINC ALLOYS • TIN ALLOYS • LEAD ALLOYS	not intended for injection molding
HI 4. Cast Metal (Investment Casting)	TBD	High	Aluminum 60-100 (RMS) Beryllium Copper 60-100 Cobalt Chrome 80-100 300 Series Stainless 90-125 Carbon Steel 90-125 400 Series Stainless 100-125	thermoplastics	Up to 1.000" ±.005" Up to 2.000 ±.010" Up to 3.000" ±.015" Up to 4.000" ±.019" Up to 5.000" ±.022" Up to 6.000" ±.025"	1" - 24"	limitation is in the ability to make sharp corners well, and very small features are difficult. Limited by laser beam size	TBD	1,000 & Up	Ceramics	TBD
HI 5. Rapid Patter Based Powder Sintering (RPBPS)	metal HRc 30 - 50 ceramic HRc 40 - 70	High	Ra 3 mm	metals, ceramics, composites, and plastics	1 - 2 mm/in	no size limitations	no geometric limitations	High injection pressures	> 20,000	powdered metals, ceramics, and other materials with special binders	used for a wide range of injection temperatures
HI 6. RSP	HRc 56 as deposited to HRc 62 age hardened	High	0.08 mm	thermoplastics	± 0.00025 in / in	8 x 8 x 4 in	> 2:1 crevices in ceramic are difficult to fill	same as normal injection moldings	millions	cast ingot	same as normal injection moldings
HI 7. Polysteel	Rc 35 to 70	High	Ra 0.05 mm	30% glass filled	± 0.005 mm / 25 mm	24 x 24 x 6 in	no geometric limitations	same or higher than normal injection moldings	> 1,000,000	proprietary	315.5 °C
HI 8. Spray Metal Deposition	Rc 50	High	8.1 mm	thermoplastics, metals	± 8.1 mm	41.7 x 78.4 x 24 in	limited by standard machine bed, process has no limits to size, customers have customized enclosure	low resistance to impact or point loading	10 to millions	high grade tool steel powders; can also deposit onto lower cost or high conductivity preforms	same or higher than normal injection moldings
HI 9. EcoTool	comparable to low alloy steel	Medium	1.8 mm (similar to fine spark eroded surface)	Wide range of materials especially polymers and metals	± 0.0007 in/in	12 x 12 x 7 in	long thin sections are difficult	comparable to a low alloy steel	> 10,000	Powdered steels, alloyed, and low alloyed, not recyclable	comparable to a low alloy steel
HI 10. Spray Metal Tooling	Rn 52	High	depends on quality of pattern, conventional	thermoplastics, metals	± 0.002 in/in	500 to 2000 mm	> 3:1 crevices in pattern are difficult to fill	low relative strength = low injection pressures	50 to 1000	wire formed materials	Low thermal properties due to epoxy backing or low melting point alloy.

APPENDIX A. TECHNICAL ATTRIBUTES

Technique Name	Surface Hardness	Impact Strength	Surface Roughness	Materials Molded	Tolerances	Tool Size Limitations	Complexity	Injection Pressures	Acceptable Quantities	Tool Materials	Thermal Properties
SI 1. RTV Molding	Shore D [illegible] - 82	Low	10 to 50 mm	One or Two part liquid urethane	± 0.005 in. for first inch ± 0.002 in. for every inch after	n/a	can include undercuts and slight negative draft	Protocam uses a process where the molds don't see injection pressures because the molds are gravity filled	10 to 50	Rubber Silicone, urethanes	low thermal properties
SI 2. Aluminum-Filled Epoxy Molding	Shore D 80 - 86	Low to Medium	high finish possible, dependant on pattern	Thermoplastics	+- 0.002 in	n/a	n/a	low relative strength = low injection pressures	Complex part: 100s Simple part: 1000s	Aluminum Filled Epoxy	315 °C
SI 3. RMT (SwifTool)	35 Vickers	Low to Medium depending on the molding material	light spark	thermoplastics, rubbers, ceramics planned	0.1 mm	23 x 24 x 8 in	use steel inserts for high aspect ratio or unsupported features	same as normal injection moldings	10 to 50,000	proprietary composite materials	same as normal injection moldings
[illegible]	[illegible] DISCONTINUED										
HI 1. Cast Metal (Sand)	Rc 48	Medium	60 to 90 mm	thermoplastics	± 0.005 in	30 x 30 x 12 in	no geometric limitations	same as normal injection moldings	500 - 1000s	Kirksite (zinc - aluminum alloy)	same as normal injection moldings
HI 2. Cast Metal (Rubber)	TBD	Low	TBD	thermoplastics	TBD	TBD	moderate complexity available	not intended for injection molding	TBD	Plaster	not intended for injection molding
HI 3. Cast Metal (Spin Casting)	[illegible]	Medium to High	TBD	QUICK-SETTING LIQUID THERMOSETS	± 0.005-.008 in/in	12 x 8 x 3 in	moderate complexity available	not intended for injection molding	1000-1200 components per hour	ZINC ALLOYS • TIN ALLOYS • LEAD ALLOYS	not intended for injection molding
HI 4. Cast Metal (Investment Casting)	TBD	High	Aluminum 80-100 (RMS) Beryllium Copper 90-100 Cobalt Chrome 80-100 [illegible] [illegible] Stainless 90-125 Carbon Steel 90-125 [illegible] [illegible] Stainless 100-125	thermoplastics	Up to 1.000" ±.005" Up to 2.000" ±.010" Up to 3.000" ±.015" Up to 4.000" ±.019" Up to 5.000" ±.022" Up to 6.000" ±.025"	11 - 24	limitations are in the ability to make sharp corners well, and very small features are difficult. Limited by laser beam size	TBD	1,000 & Up	Ceramics	TBD
HI 5. Rapid Patter Based Powder Sintering (RPBPS)	metal - Rc 40 - 50 ceramic - Rc 40 - [illegible]	High	Ra [illegible] mm	metals, ceramics, composites and plastics	1 - 2 mm/in	no size limitations	no geometric limitations	High injection pressures	[illegible]	powdered metals, ceramics, and other materials with special binders	used for a wide range of injection temperatures
HI 6. RSP	HRc 56 as deposited to HRc 60 age hardened	High	0.03 mm	thermoplastics	± 0.00025 in/in	5 x 8 x 4 in	> 0.1" crevices in ceramic are difficult to fill	same as normal injection moldings	millions	cast ingot	same as normal injection moldings
HI 7. Polysteel	Rc 35 to 70	High	Ra 0.25 mm	30% glass filled	± 0.005 mm/125 mm	24 x 24 x 6 in	no geometric limitations	same or higher than normal injection moldings	> 1,000,000	proprietary	315.5 °C
HI 8. Spray Metal Deposition	Rc 50	High	0.1 mm	thermoplastics, metals	± 0.1 mm	41.7 x 78.4 x 24 in	limited by standard machine bed, process has no limits to size, customers have customized enclosure	low resistance to impact or point loading	10 to millions	high grade tool steel powders, can also deposit onto lower cost or high conductivity preforms	same or higher than normal injection moldings
HI 9. EcoTool	comparable to low alloy steel	Medium	finish is similar to fine spark eroded surfaces	Wide range of materials especially polymers and metals	± 0.0007 mm	12 x 12 x 7 in	long thin sections are difficult	comparable to a low alloy steel	[illegible]	Powdered steels, alloyed and low alloyed, not recyclable	comparable to a low alloy steel
HI 10. Spray Metal Tooling	Rc 50	High	depends on quality of pattern	thermoplastics, metals	± 0.002 mm	500 to 2000 mm	> 0.1" crevices in pattern are difficult to fill	low relative strength = low injection pressures	50 to 1000	wire form metal alloys	low thermal properties due to epoxy backing or low melting point alloy

Technique Name	Surface Hardness	Impact Strength	Surface Roughness	Materials Molded	Tolerances	Tool Size Limitations	Complexity	Injection Pressures	Acceptable Quantities	Tool Materials	Thermal Properties
HI 11. 3D Keltool	Rc 32 heat treated to Rc 42 - 46	High	20 to 25 min	Thermoplastics	0.025 mm/in. with details to 0.04 mm	5 x 8.5 x 5 in	limits on aspect ratio, typical molding limitations	20,000 to 25,000 psi	50 to millions	A6 tool steel / tungsten carbide alloy	max temp 650°C
HI 12. Stratoconception	Same as traditional tools can achieve	Medium to High	same as a CNC process can achieved	polypropylene, PET and aluminum alloy but really any can be used	same tolerances than traditional tools can be achieved.	No size or build limitation. But not dedicated to very small parts	very small detail can be difficult to obtain.	The same industrial molding parameters can be used.	500 to 15,000	wood, polymer resin, aluminum, tool steel (H11, C45E, . .)	The same industrial molding parameters can be used.
HI 13. Plasma Spray	$Hv_{0.025}$ 404.9	High	< 0.15 mm	thermoplastics, metals	± 0.05 mm	n/a	difficult or impossible for narrow slots or deep holds	40 to 100 Mpa before detachment of spray layer	Over 10,000	Ceramic and metal powders, Stainless steel, Fe-Cr alloy	The higher the melting point of the spray metal the higher the thermal properties of the mold
HI 14. Metal Copy	TBD	High	0.05 to 1 mm	thermoplastics, metals	0.1 mm	4.72 x 4.72 x 2.76	no geometric limitations	High injection pressures	50,000 to 100,000	steel alloy	excellent heat conductivity
HD 11. Laser Tool	HV_{30} 490	High	30 and 40 mm	Thermoplastics	dimensional accuracy can be increased by pre and post processing technology	TBD	Large and complex parts	High injection pressures	TBD	TBD	TBD
HI 15. Nickel Electroforming	TBD	High	3 - 5 min	thermoplastics, metals	extreme accuracy	25 x 8 ft	Good complexity although under cuts and small slits or holes could be difficult	High strength for high pressure applications	TBD	epoxy resin and mainly nickel	same as normal injection moldings
HI 16. Nickel Vapor Deposition	TBD	High	TBD	thermoplastics, metals	extreme accuracy	TBD	Good complexity although under cuts and small slits or holes could be difficult	High strength for high pressure applications	TBD	nickel carbonyl gas atmosphere with main material being nickel and backfilled with proprietary material	same as normal injection moldings
HI 17. Fused Metallic Core	TBD	High	TBD	thermoplastics	TBD	1" - 24"	limitation is in the ability to make sharp corners well, and very small features are difficult	not intended for injection molding	TBD	Low melting point alloys	not intended for injection molding
SD 2. Direct AIM	Rb 87	Low	500 min as processed 88 min after finishing	Thermoplastics Aluminum-filled epoxy Ceramics Low-melt temperature metals	± 0.002 in/in	14 x 12 x 17 in	TBD	TBD	10 to 50	TBD	Poor heat conductivity
HD 1. Laser Sintering of Silica Sand	Hv 105 117	Medium to High	vertical = 26.2 mm horizontal = 35 mm	thermoplastics	± 0.4 mm	2.36 x 2.36 x 1 in	Large and complex parts	same as normal injection moldings	1000s	Silica Sand Si, Zr, Ti, Ca, Al, Ba, Fe, Cs, Mg, I, K, Cr, Pd, Cl, Cu, Zn, S, P	same as normal injection moldings
HD 2. SLS	Shore D - 2240	Low	Ra 7.5 to 50	thermoplastics	± 0.115 to 0.250 mm / 25mm	8 x 10 x 5 in	Large and complex parts	low injection pressures	> 500	420 stainless powder and bronze infiltrate, A6 steel composite and proprietary infiltrate	parts with glass filling have a much higher thermal resistance
HD 3. DMLS	$Hv_{0.025}$ 450 - 1000	Medium to High	up to Ra 9 mm as sintered and up to Ra 3 mm after shot peening	thermoplastics	± 0.002 in/in	9.8 x 9.8 x 7.3 in	minimum wall thickness 0.6 mm	Comparable to conventional tool steel, and bronze-based broadly comparable to aluminum	1000 to 1,000,000	metal powder blends (420 stainless steel and bronze infiltrate)	Comparable to conventional tool steel, and bronze-based broadly comparable to aluminum
HD 4. 3D Printing	Excellent	Medium to High	20 - 40 mm after infiltration 15 mm	thermoplastics, metals	0.005 in + 0.002 in/in	40 x 20 x 10 in	"builds the impossible"	good range of injection pressures allowable	> 1000	Any material that can be found in powder form	good range of thermal properties allowable
HD 5. Rapid Tool	Rb 87	Medium or High depending on molding material	5 mm	thermoplastics, metals	0.005 to 0.01 in	8 x 10 x 5 in	Intricacy is no problem	same as normal injection moldings	100,000 most plastics 100s Zn, Al, Mg	Tool Steel	same as normal injection moldings

Technique Name	Surface Hardness	Impact Strength	Surface Roughness	Materials Molded	Tolerances	Tool Size Limitations	Complexity	Injection Pressures	Acceptable Quantities	Tool Materials	Thermal Properties
HD 6. LOM	slightly harder than wood	Low	very smooth	sand casting	± 0.01 in	machine limits. 32 x 22 x 20in.	not intended for injection molding	not intended for injection molding	< 100	adhesive paper	not intended for injection molding
HD 7. High Speed / Laser Milling	26 - 37 Rc	Medium or High depending on molding material	tool marks must be polished out, dependant on tool and code	ABS materials and filled polymers	± 0.025 mm / 25mm	n/a	external radii in tool must be hand finished	same as normal injection moldings	50 to 100,000	Tool Steel, aluminum	same as normal injection moldings
HD 8. LENS	Rc 45 to 60	High	5.1 to 7.6 mm	thermoplastics, metals	+/- 0.125 mm/25mm	12 x 12 x12 in. 18 x 18 x 18 in. 60 x 36 x 36 in	lower hemisphere of movement	same as normal injection moldings	> 1,000,000	powdered metals including tool steels, stainless steels including 420, titanium, Inconel, and others	same as normal injection moldings
HD 9. ProMetal	Rc 26 to 30	Medium or High depending on molding material	6.4 to 10.2 mm	thermoplastics	0.005 in. + 0.002 in/in	40 x 20 x 10	can have sections as thin as 1.25 mm, high strength for handling	good range of injection pressures allowable	> 10 aluminum forging <1000 aluminum die casting > 100,000 PIM	stainless steel and bronze, Inconel, aluminum or gold	good range of thermal properties allowable
HD 10. LLCC	Same as traditional tools can achieve	Medium to High	same as a CNC process can achieved	thermoplastics	same tolerances than traditional tools can be achieved.	No size or build limitation. But not dedicated to very large parts	undercuts may be difficult to produce, vertical non-supported sections may be difficult	The same industrial molding parameters can be used.	500 to 15,000	thin metal sheets	The same industrial molding parameters can be used.

Note: Green column, impact strength, is due to the unknown nature of the impact strength of all processes. Therefore an educated guess has been made based on the number of parts per mold, the main materials in the process and the surface hardness of the tool. (highlighted to stand out)

Note: Any yellow boxes remaining are highlighted to demonstrate the unknown nature of the values for those specific cells. In all cases the companies and/or universities doing the research of production of that particular process have all been contacted multiple times with no responses.

Note: SWIFT is highlighted red to present itself as thrown out due to the discontinuation of the research on the process and the discontinuation of funding for the project.

APPENDIX B. BUSINESS ATTRIBUTES

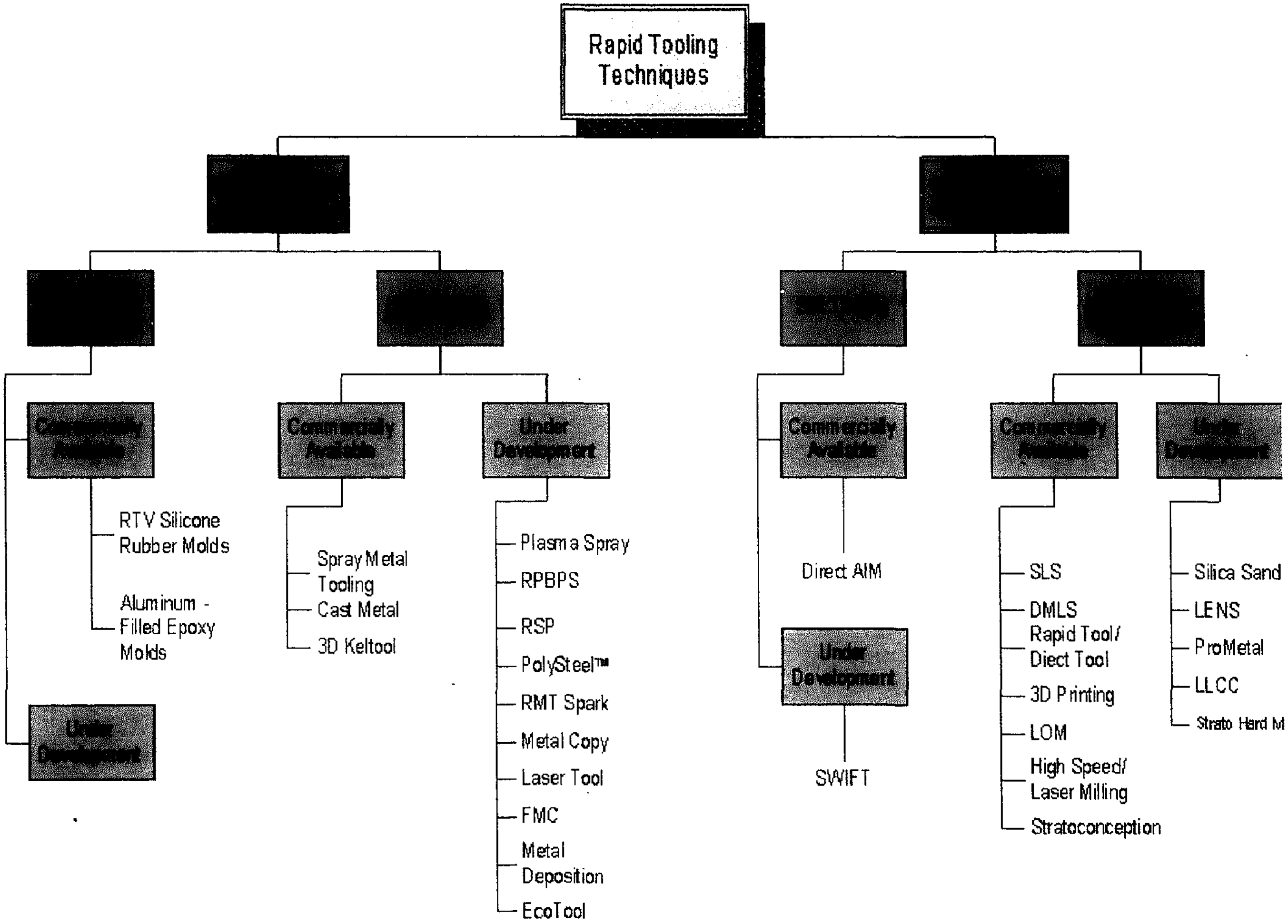
Technique Name	Lead Time	Suppliers	Acceptable Quantities	Relative Cost	Process Maturity	Availability
SI 1. RTV Molding	0.5 to 2 weeks	various	10 to 50	$1000 - $5000	Readily Available	Commercially available with purchase of necessary equipment also inhouse work done
SI 2. Aluminum-Filled Epoxy Molding	1 to 4 weeks	various	Complex part 100s Simple part 1000s	Typically $3000 Range. $2500 to $10,000 up to $35,000	Readily Available	Commercially available with purchase of necessary equipment also inhouse work done
SI 3. RMT (SwifTool)	1 day to 1 week	Rapid Moulding Technologies, LTd	10 to 50,000	Depends on size of part / tool	Available but making advancements in technology	Under development awaiting new patent
SD 1. SWIFT	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
HI 1. Cast Metal (Sand)	3 to 6 weeks	various	500 - 1000s	$4000 to $15000	Readily Available	Commercially available with purchase of necessary equipment
HI 2. Cast Metal (Rubber)	TBD	TBD	TBD	TBD	Readily Available	Commercially available with purchase of necessary equipment
HI 3. Cast Metal (Spin Casting)	4 hrs - 2 days	Various	1 & Up	$35 to $250	Readily Available	Commercially available with purchase of necessary equipment
HI 4. Cast Metal (Investment Casting)	8 - 16 wks	Various	1,000 & Up	$1,000 to $25,000	Readily Available	Commercially available with purchase of necessary equipment
HI 5. Rapid Patter Based Powder Sintering (RPBPS)	< 2 weeks	Drexel University	> 20,000	< $1000	Available but making advancements in technology	Under development awaiting patent and further testing
HI 6. RSP	1 week	RSP Tooling LLC	millions	$1500 - $2000	Available but making advancements in technology	Under development awaiting new patent
HI 7. Polysteel	1 to 3 weeks	Dynamic Tooling	> 1,000,000	$7000 to $10,000	Available but making advancements in technology	Under development awaiting new patent
HI 8. Spray Metal Deposition	1 to 2 days depending on workload	PCM Inc	10 to millions	Depends on size of part / tool	Available but making advancements in technology	Under development awaiting new patent
HI 9. EcoTool	2 days	TNO Industrial Technology (available 2005)	> 10,000	Depends on size of part / tool	Available but making advancements in technology	Under development awaiting new patent
HI 10. Spray Metal Tooling	2 to 4 weeks	various	50 to 1000	$2000 to $15,000	Readily Available	Commercially available with purchase of necessary equipment
HI 11. 3D Keltool	1 - 5 weeks	3D Systems and Licensees	50 to millions	$2000 to $5000	Limited Availability	Commercially available with purchase of necessary equipment also inhouse work done
HI 12. Stratoconception	1 to 10 weeks	CIRTES	500 to 15,000	typically $4,826.46	Available but making advancements in technology	Commercially available with purchase of necessary equipment
HI 13. Plasma Spray	1 week	Tsinghua University, Beijing	Over 10,000	$250 dollars	Late stages of development	Under development awaiting new patent
HI 14. Metal Copy	2 weeks	Prototal	50,000 to 100,000	53% that of traditional milling	Available but making advancements in technology	Under development awaiting new patent
HD 11 Laser Tool	TBD	TBD	TBD	TBD	Available but making advancements in technology	Under development awaiting new patent
HI 15. Nickel Electroforming	TBD	Various	TBD	TBD	Available but making advancements in technology	Under development awaiting new patent

APPENDIX B. BUSINESS ATTRIBUTES

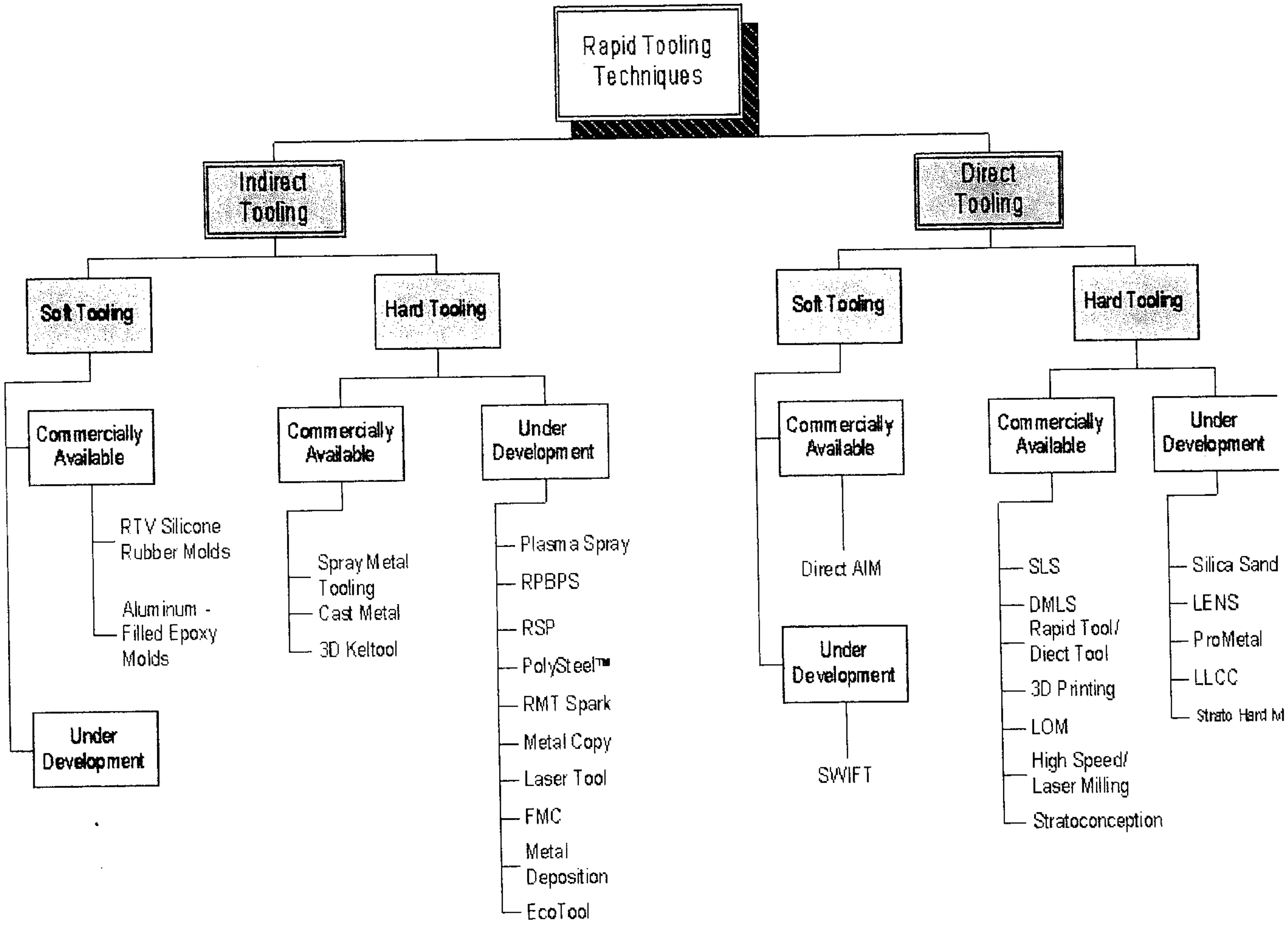
Technique Name	Lead Time	Suppliers	Acceptable Quantities	Relative Cost	Process Maturity	Availability
SI 1. RTV Molding	0.5 to 2 weeks	various	10 to 50	$1000 - $5000	Readily Available	Commercially available with purchase of necessary equipment also inhouse work done
SI 2. Aluminum-Filled Epoxy Molding	1 to 4 weeks	various	Complex part 100s Simple part 1000s	Typically $3000 Range $2500 to $10,000 up to $35,000	Readily Available	Commercially available with purchase of necessary equipment also inhouse work done
SI 3. RMT (SwifTool)	1 day to 1 week	Rapid Moulding Technologies, LTd	10 to 50,000	Depends on size of part / tool	Available but making advancements in technology	Under development awaiting new patent
SD 1. SWIFT	[illegible]					
HI 1. Cast Metal (Sand)	3 to 5 weeks	various	500 - 1000s	$4000 to $15000	Readily Available	Commercially available with purchase of necessary equipment
HI 2. Cast Metal (Rubber)	TBD	TBD	TBD	TBD	Readily Available	Commercially available with purchase of necessary equipment
HI 3. Cast Metal (Spin Casting)	4 hrs - 2 days	Various	1 & Up	$35 to $250	Readily Available	Commercially available with purchase of necessary equipment
HI 4. Cast Metal (Investment Casting)	8 - 16 wks	Various	1,000 & Up	$1,000 to $25,000	Readily Available	Commercially available with purchase of necessary equipment
HI 5. Rapid Patter Based Powder Sintering (RPBPS)	< 2 weeks	Drexel University	> 20,000	< $1000	Available but making advancements in technology	Under development awaiting patent and further testing
HI 6. RSP	1 week	RSP Tooling LLC	millions	$1500 - $2000	Available but making advancements in technology	Under development awaiting new patent
HI 7. Polysteel	1 to 5 weeks	Dynamic Tooling	> 1,000,000	$7000 to $10,000	Available but making advancements in technology	Under development awaiting new patent
HI 8. Spray Metal Deposition	1 to 2 days depending on workload	PCM Inc	10 to millions	Depends on size of part / tool	Available but making advancements in technology	Under development awaiting new patent
HI 9. EcoTool	2 days	TNO Industiral Technology (available 2005)	> 10,000	Depends on size of part / tool	Available but making advancements in technology	Under development awaiting new patent
HI 10. Spray Metal Tooling	2 to 4 weeks	various	50 to 1000	$2000 to $15,000	Readily Available	Commercially available with purchase of necessary equipment
HI 11. 3D Keltool	1 - 6 weeks	3D Systems and Licensees	50 to millions	$2000 to $5000	Limited Availablity	Commercially available with purchase of necessary equipment also inhouse work done
HI 12. Stratoconception	1 to 10 weeks	CIRTES	500 to 15,000	typically $4,826.46	Available but making advancements in technology	Commercially available with purchase of necessary equipment
HI 13. Plasma Spray	1 week	Tsinghua University, Beijing	Over 10,000	$250 dollars	Late stages of development	Under development awaiting new patent
HI 14. Metal Copy	2 weeks	Prototal	50,000 to 100,000	53% that of traditional milling	Available but making advancements in technology	Under development awaiting new patent
HD 11.Laser Tool	TBD	TBD	TBD	TBD	Available but making advancements in technology	Under development awaiting new patent
HI 15. Nickel Electroforming	TBD	Various	TBD	TBD	Available but making advancements in technology	Under development awaiting new patent

Technique Name	Lead Time	Suppliers	Acceptable Quantities	Relative Cost	Process Maturity	Availability
HI 16. Nickel Vapor Deposition	TBD	TBD	TBD	TBD	Available but making advancements in technology	Under development awaiting new patent
HI 17. Fused Metallic Core	TBD	TBD	TBD	TBD	Available but making advancements in technology	Under development awaiting new patent
SD 2. Direct AIM	1 week	3D Systems and SB's	10 to 50	$2000 to $5000	Readily Available	Commercially available with purchase of necessary equipment also inhouse work done
HD 1. Laser Sintering of Silica Sand	22 hours	National University of Singapore	1000s	Depends on size, typically $1 per cm3	Late stages of development	Under development awaiting new patent
HD 2. SLS	1 to 5 days	3D Systems and SB's	> 500	$1500 to $2000	Readily Available	Commercially available with purchase of necessary equipment also inhouse work done
HD 3. DMLS	1 to 4 weeks	EOS GmbH	1000 to 1,000,000	$175 to $185 per kg	Readily Available	Commercially available with purchase of necessary equipment also inhouse work done
HD 4. 3D Printing	1 week	Z Corp	> 1000	$1.80 per cubic in for material cost + Labor machine purchase $25,000, $56,000, $180,000	Readily Available	Commercially available with purchase of necessary equipment also inhouse work done
HD 5. Rapid Tool	2 to 5 weeks	3D Systems	100,000 most plastics 100s Zn, Al, Mg	$4000 to $10,000	Readily Available	Commercially available with purchase of necessary equipment also inhouse work done
HD 6. LOM	3 to 8 hours per inch thickness	Cubic Technologies	< 100	$50 per hour	Readily Available	Commercially Available
HD 7. High Speed / Laser Milling	2 to 6 weeks	various	50 to 100,000	$4000 to $25,000	Readily Available	Commercially available proprietary process
HD 8. LENS	2 to 4 weeks	Optomec and SB's	> 1,000,000	Depends on size of part / tool	Available but making advancements in technology	Under Development
HD 9. ProMetal	1 week	Extrude Hone, Prometal Div	> 10 aluminum forging < 1000 aluminum die casting > 100,000 PIM	Depends on size of part / tool	Readily Available	Commercially available with purchase of necessary equipment also inhouse work done
HD 10. LLCC	1 to 10 weeks	CRF	500 to 15,000	typically $4,826.46	Available but making advancements in technology	Under development awaiting new patent

APPENDIX C. CLASSIFICATION OF THE RAPID TOOLING TECHNIQUES



APPENDIX C. CLASSIFICATION OF THE RAPID TOOLING TECHNIQUES



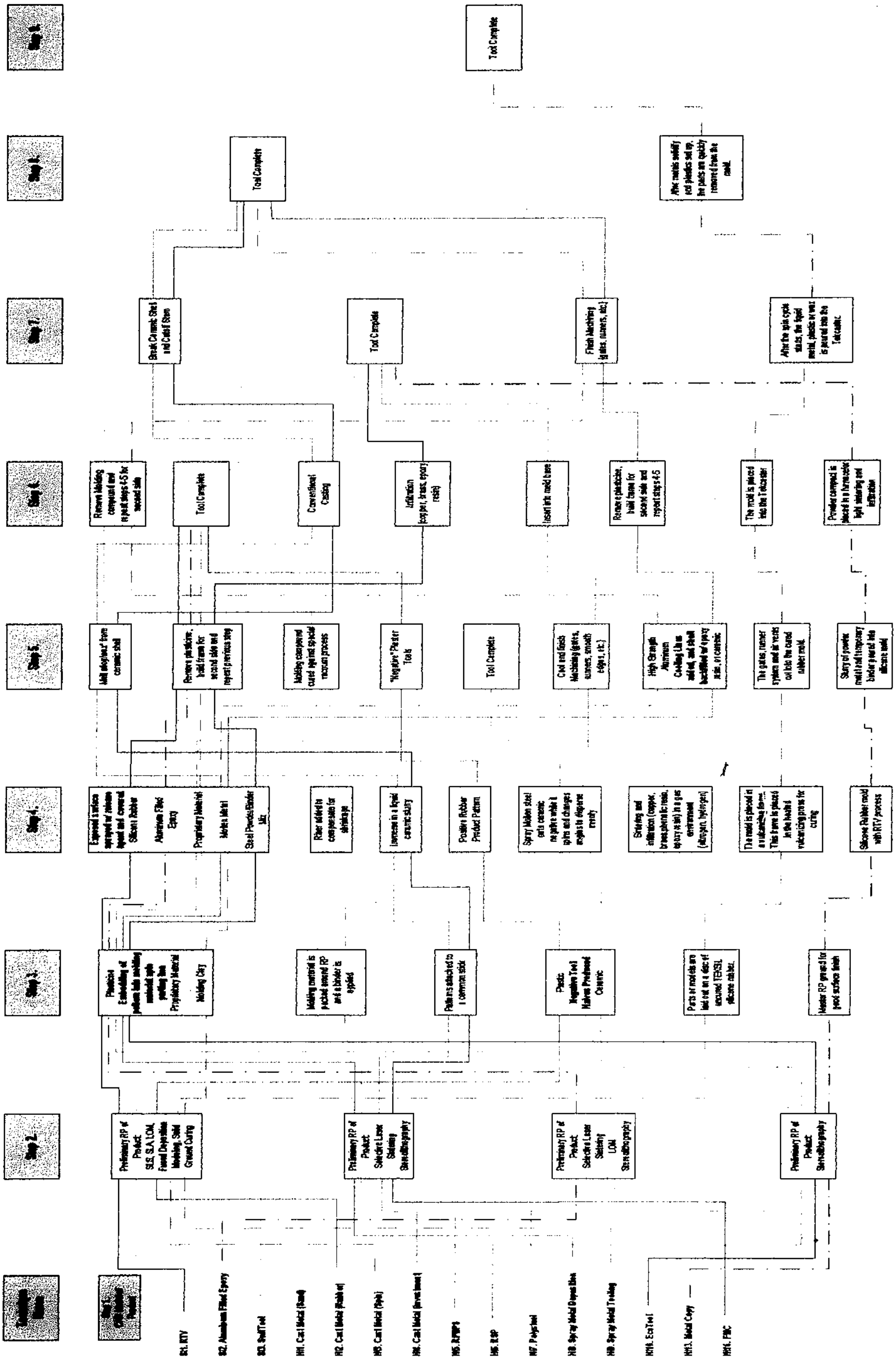
APPENDIX D. PROCESS STEPS FOR EACH TECHNIQUE

Technique Name	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7	Step 8	Step 9	Notes
SI 1. RTV Molding	CAD Drawing of Product	RP of Product SLS, LOM,SLA, Fused Deposition Modeling, Solid Ground Curing	Embedding in plasticine to parting line (mold box)	Exposed Surface covered with silicone rubber and cured	Remove plasticine, build frame for 2nd side, repeat previous step for 2nd side	Tool Complete				
SI 2. Aluminum-Filled Epoxy Molding	CAD Drawing of Product	RP of Product SLS, LOM, SLA	Embedding in plasticine to parting line	Exposed Surface sprayed with release agent and filled with aluminum filled epoxy and cured	Remove plasticine, build frame for 2nd side, repeat previous step for 2nd side	Tool Complete				
SI 3. RMT (SwifTool)	CAD Drawing of Product	RP of Product SLS, SLA	Embedding in claylike molding compound	Exposed surface sprayed with release agent and filled with proprietary fiber-filled thermoset composite material	Cured against the model in a special vacuum press	Remove molding compound and repeat previous steps for 2nd side	Finish Machining ie runners, gates, sprue, etc	Tool Complete		
SD 1 SWIFT	CAD Drawing of Product	Sheets of ABS is fed through a laser printer which prints a high density polyethylene which acts as a mask	Acetone solvent is applied to the bottom of the sheet and pressed on top of the existing sheets, while solvent welds take place (Note)	Shell milling cutter mills down the thickness to correct any minor variations in thickness	CNC machine layer cross-sectional contour	Repeat steps 2 - 5 till all layers are complete	Tool Complete			Acetone dissolves the ABS sheet not guarded by HDPE
HI 1. Cast Metal (Sand)	CAD Drawing of Product	RP of Product SLS, LOM,SLA, Fused Deposition Modeling, Solid Ground Curing	Molding material is packed around the RP and a special binder is applied to packed material	A void is added, called a riser, to compensate for shrinkage	Tool Complete					
HI 2. Cast Metal (Rubber)	CAD Drawing of Product	RP of Product SLS, LOM, SLA, Fused Deposition Modeling, Solid Ground Curing	"Negative" Plastic Tool Halves	"Positive" Rubber Product Pattern	"Negative" Plaster mold Halves	Tool Complete				
HI 3. Cast Metal (Spin Casting)	CAD Drawing of Product	RP of Product SLS, LOM, SLA, Fused Deposition Modeling, Solid Ground Curing	Parts or models are laid out on a disc of uncured TEKSIL silicone rubber	The mold is placed in a vulcanizing frame. This frame is placed in the heated vulcanizing press for curing.	The gates, runner system and air vents are easily cut into the cured rubber mold with a sharp knife or scalpel.	The mold is placed into the Tekcaster	After the spin cycle starts, the liquid metal, plastic or wax is poured into the Tekcaster.	After metals solidify and plastics set up, the parts are quickly removed from the mold.	Tool Complete	
HI 4. Cast Metal (Investment Casting)	CAD Drawing of Product	RP of Product stereolithography, SLS (WAX)	Patterns attached to a common stick	Immerse in a liquid ceramic slurry	Melt wax from ceramic shell	Conventional Casting	Break Ceramic Shell and Cutoff Stem	Tool Complete		
HI 5. Rapid Patter Based Powder Sintering (RPBPS)	CAD Drawing of Product	RP of Product Stereolithography	Pattern is positioned on a substrate in a frame and a mixture of metal/ceramic powder and binder is cast around the pattern at certain pressure	The "green" part is then sintered and infiltrated in a protective environment (Note)	Tool Complete					Gas used is typically either nitrogen or hydrogen. Infiltrants - copper, brass, phenolic resin, epoxy resin
HI 6 RSP	CAD Drawing of Product	RP of Product Stereolithography	Ceramic Mold or negative is produced	Spray Molten steel onto ceramic negative while it spins and change angle to distribute evenly	Allowed to cool for 90 mins and then finish machined to smooth edges and cut extra material	Inserted into mold base	Tool Complete			
HI 7. Polysteel	CAD Drawing of Product	RP of Product SLS, LOM, SLA	Embedding in plasticine to parting line	Exposed surface sprayed with release agent and filled with proprietary metals and allowed to cure (Note)	Remove plasticine, build frame for 2nd side, repeat previous step for 2nd side	Tool Complete				Metal used has 3 grades Polysteel I, II, III
HI 8. Spray Metal Deposition	CAD Drawing of Product	RP of Product SLS, SLA	Embedding in plasticine to parting line and sprue, gates and ejector pins are added	Exposed Surface sprayed with release agent and a 2 -3 mm thick shell of low temperature molten metal is deposited over it	Cooling lines are added	Shell is back filled with epoxy resin or ceramic to improve strength	Remove plasticine build frame for 2nd side, repeat previous steps for 2nd side	Finish Machining ie. runners, gates, sprue, etc	Tool Complete	
HI 9 EcoTool	CAD Drawing of Product	RP of Product Stereolithography	Embedding in plasticine to parting line	Exposed surface sprayed with release agent and filled with steel powder binder system, and cures at room temperature	Remove plasticine, build frame for 2nd side, repeat previous step for 2nd side	Infiltration both halves	Tool Complete			

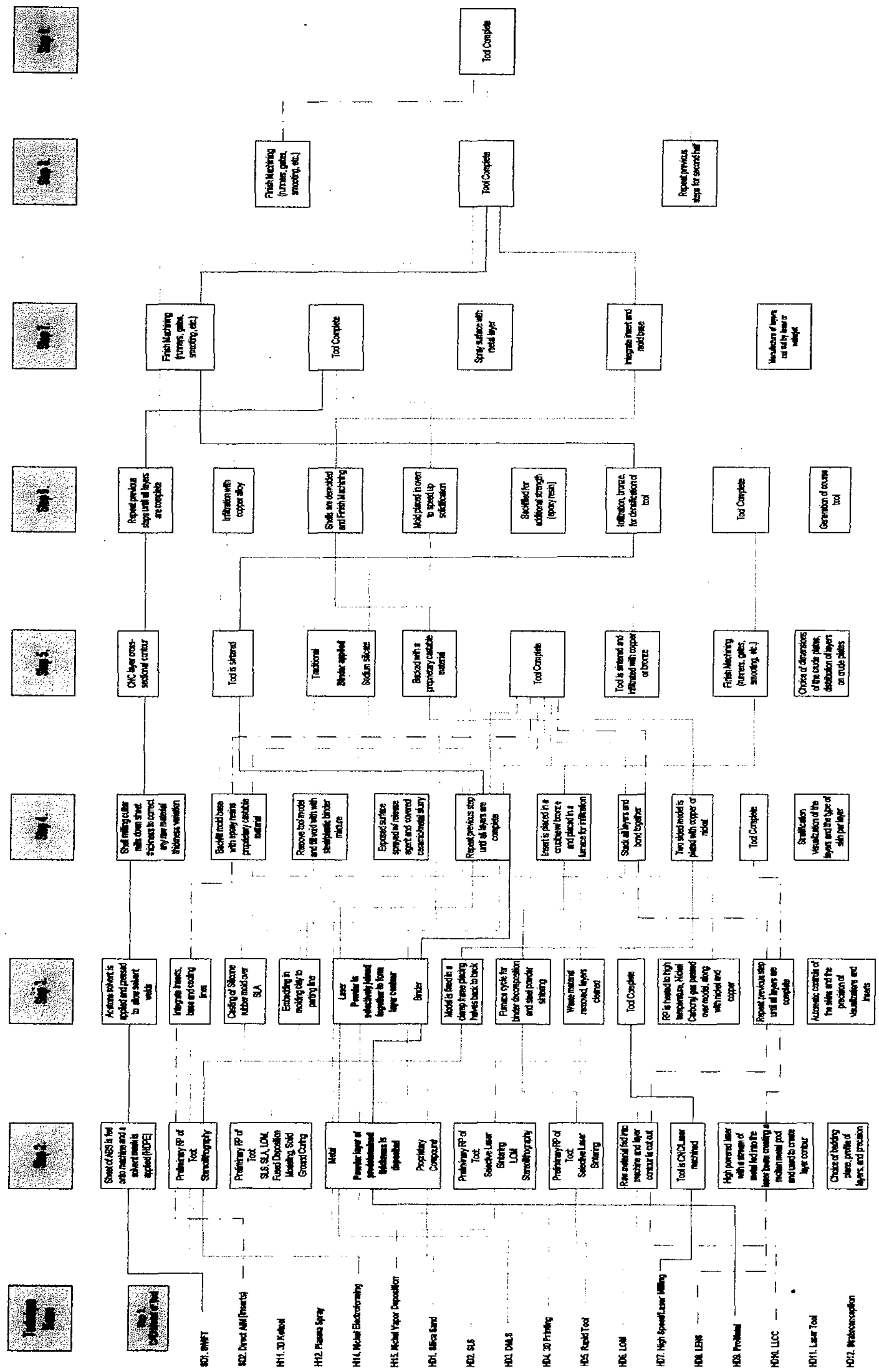
Technique Name	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7	Step 8	Step 9	Notes:
HI 10 Spray Metal Tooling	CAD Drawing of Tool	RP of Tool: SLS, SLA, LOM, Fused Deposition Modeling, Solid Ground Curing	Embedding in molding clay to parting line aluminum frame is built to absorb molding pressures	Exposed surface sprayed with a release agent and sprayed with metal	Cooling lines are added and any additional supports	High Strength aluminum filled epoxy is used as a back filling material or low melting point alloy	Remove molding clay, repeat steps 4-6 for 2nd half	Finish Machining: ie runners, gates, sprue, etc..	Tool Complete	
HI 11. 3D Keltool	CAD Drawing of Tool	RP of Tool Stereolithography	Casting of silicone rubber mold over SLA tool	Remove tool model and fill void left by tool model with steel/plastic binder mixture (green part)	Green part is removed and sintered	Infiltration with copper alloy	Finish Machining ie. runners, gates, sprue, etc	Tool Complete		
HI 12 Stratoconception	CAD Drawing of Tool and Generation of STL file	Choice of bedding plane, profile layer, precision, report ratio of scale	Automatic controls of the skins and the precision, visualization and installation of the inserts	Stratification visualization of the layers and the type of skin per layer	Choice of dimensions of the crude plates, distribution of the layers on crude plates	Generation of the course tool	Manufacture of layers, cut out by a laser or water jet cut 3 - 5 axis machine	Assembly of layers and finish machining	Tool Complete	
HI 13. Plasma Spray	CAD Drawing of Tool	RP of Tool: SLS, SLA, LOM, Fused Deposition Modeling, Solid Ground Curing	Embedding in molding clay to parting line	Exposed surface sprayed with release agent and ceramic/metal slurry sprayed onto exposed half	Binders are sprayed onto slurry	Once slurry has cured the tool half is backfilled for additional strength	Spray on Surface layer of metal	remove molding clay and repeat steps 4 - 7 for 2nd half	Tool Complete	
HI 14. Metal Copy	CAD Drawing of Product	RP of Product: Stereolithography	The master RP is manually grinded to obtain good surface finish	Build a silicone mold with RTV process	A slurry of powder metal and temporary binder are poured in the silicone mold	The powder compact is placed in a furnace where it is subjected to light sintering and infiltration	Tool Complete			
HD 11 Laser Tool	CAD Drawing of Tool	Powder is deposited on a steel platform by wipers with a layer thickness = 0.05mm	Laser moves over powder and sinters the powder, creating layer contour desired	Repeat previous steps until tool complete	Finish Machining: ie. runners, gates, sprue, etc	Tool Complete				
HI 15 Nickel Electroforming	CAD Drawing of Tool / Product (NOTE. plating mandrel applied)	RP of Tool/Product: Stereolithography	The model is precisely fixed in a standard sized clamp frame, placing both halves back to back	The two sided model is plated with copper or nickel	Backing with a high strength proprietary castable material and cured	Shells are demolded and finish machined	Tool inserts placed in mold bases	Tool Complete		Plating mandrel applied in CAD drawing by company
HI 16 Nickel Vapor Deposition	CAD Drawing of Tool	RP of Tool SLA, SLS, LOM	The RP pattern is heated to high temperatures and nickel carbonyl gas is passed over the pattern	As the gas is passed over the pattern a layer of nickel is deposited on the pattern	Backfilled with proprietary castable material	Tool Complete				
HI 17 Fused Metallic Core	CAD Drawing of Product	RP of Product: stereolithography, SLS (low melting point alloy)	Patterns attached to a common stick	Immerse in a liquid ceramic slurry	Melt alloy from ceramic shell	Conventional Casting	Break Ceramic Shell and Cutoff Stem	Tool Complete		
SD 2 Direct AIM	CAD Drawing of Tool inserts	Use of stereolithography for production of tool inserts	integrate tool inserts into base mold and add cooling lines	Backfill mold with epoxy resins allow to cure	Tool Complete					
HD 1 Laser Sintering of Silica Sand	CAD Drawing of Tool	Base layer of silica sand and sodium silicate solution laid out on base plate	CO2 Laser selectively sinters the sand particles according to the cross section of the powder layer	Repeat previous steps until tool complete	A layer of sodium silicate solution is brushed on, repeat several times	Mold is placed in an oven at 200oC to speed up solidification	Tool Complete			
HD 2 SLS	CAD Drawing of Tool	Powder layers of predetermined thickness are spread on the surface of the building plate with a re-coater arm	Laser scans the slice file geometry on the powder layer	After layer is complete the build plate moves down and repeat steps 2 -4 until build is complete	Tool Complete					
HD 3 DMLS	CAD Drawing of Tool	Powder layers of predetermined thickness are spread on the surface of the building plate with a re-coater arm (metal)	Laser scans the slice file geometry on the powder layer	After layer is complete the build plate moves down and repeat steps 2 -4 until build is complete	Tool Complete					

Technique Name	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7	Step 8	Step 9	Notes:
HD 4. 3D Printing	CAD Drawing of Tool	Each layer is a thin distribution of powder spread over the powder bed surface	An "ink-jet" printer sprays a binder material selectively joining the particles where the object is	The completed layer is lowered and the next layer is built on top	Repeat steps 2-4 until build is complete	Finish build is placed in a furnace for a heat treatment and the unbound powder is removed	Tool Complete			
HD 5. Rapid Tool	CAD Drawing of Tool as an insert	RP of Tool SLS	"Green" insert is placed in furnace for 1st cycle where binder decomposes and steel powder sinters	"Brown" insert is placed in a crucible with a measured amount of bronze and placed in the furnace for infiltration	Finish Machining. ie. runners, gates, sprue, etc..	Tool Complete				
HD 6. LOM	CAD Drawing of Tool	Each layer is cut out of a piece of steel (including reference points)	The waste material is removed and the laminations are cleaned	The bond agent is applied and the laminations are stacked	Tool Complete					
HD 7. High Speed / Laser Milling	CAD Drawing of Tool cavity	Tool is CNC machined or laser machined	Tool Complete							
HD 8. LENS	CAD Drawing of Tool	High powered Nd:YAG laser focused on metal substrate creating molten metal pool increasing material volume	The metal powder is delivered through nozzles along side laser deposits layer contours	Repeat previous steps until tool complete	Tool Complete					
HD 9. ProMetal	CAD Drawing of Tool	Powdered metal is collected and spread onto the build piston	Print head applies a layer of binder to the powdered metal to form the first "slice" of part	A new layer of metal is collected while a drying lamp is applied. The part is lowered to allow the next layers to be built	Repeat steps 2-4 until build is complete	"green" part is placed in a furnace where the binder is burnt away and the steel sinters together (60% dense)	Molten bronze is infiltrated via capillary action to make the part fully dense	Finish Machining: ie. runners, gates, sprue, etc	Tool Complete	
HD 10. LLCC	CAD Drawing of Tool	Thin metal sheets fed onto cutting surface, high powered CO2 laser cuts out layer contour	Repeat previous steps until all layers are complete	Stack all layers and attach them together	Tool Complete					

APPENDIX E. "WIRING" DIAGRAM STARTING CAD MODEL OF PRODUCT



APPENDIX F. “WIRING” DIAGRAM STARTING CAD MODEL OF TOOL



VITA

Andrew Thomas Haglin, born May 18, 1981 in St. Louis, Missouri, is the son of Preston C. Haglin Jr. and M. Karen Haglin. Mr. Haglin was raised in St. Louis, Missouri and graduated from St. Louis University High before attending Lehigh University where he received his Bachelor of Science in Mechanical Engineering in May of 2003.

Mr. Haglin pursued further education in mechanical engineering at Lehigh University where he served as an assistant coach for the crew team during the four semesters to complete his Master of Science. He was also a research assistant specializing in injection molding processes, specifically rapid tooling and expert systems, in the Manufacturing Science Laboratory headed by Professor John Coulter. Mr. Haglin is a member of the American Society of Mechanical Engineers and Society of Plastics Engineers.

Upon completion of his Master of Science, Mr. Haglin will move on to the public sector as an employee of Becton Dickinson, a medical device manufacturer. He also hopes to design and build racing shells and America's Cup sailing yachts.

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