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MATERIALS PROPERTIES OF PARTS PRODUCED BY FUSED DEPOSITION MODELING RAPID PROTOTYPING TECHNOLOGY

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Abstract: *Rapid Prototyping (RP) can be defined as a group of techniques used to quickly fabricate a scale model of a part or assembly using three-dimensional computer aided design (CAD) data. What is commonly considered to be the first RP technique, Stereolithography, was developed by 3D Systems of Valencia, CA, USA. The company was founded in 1986, and since then, a number of different RP techniques have become available. In this contribution are presented basic information about basic and new materials used for realization of products by Fused Deposition Modelling RP technology application. In different Rapid Prototyping technologies the initial state of material can come in either solid, liquid or powder state. In final part of the paper is presented project of experimental part design and production with application of Rapid Prototyping technology realized by students and workers of Faculty of Manufacturing Technologies in Presov, Slovakia. In frame of part design there was model with three holes realized together with its dual part. Production of the parts was connected with realization of produced parts dimensional issues and final product assembly.*

Key words: *Rapid Prototyping, Fused Deposition Modeling, materials for rapid prototyping.*

1. INTRODUCTION

Rapid prototyping involves creating a realistic model of a product's user interface to get prospective customers involved early in the design of the product. Using rapid prototyping, you model the look and feel of the user interface without investing the time and labour required to write actual code. Then you show the prototype to prospective customers, revise the prototype to address their comments, and keep repeating these two steps. Your goal is to produce a complete, agreed-upon design of the product's user interface before writing a single line of actual code. When walkthroughs and usability tests show you that customers are delighted with your prototype user interface, then programmers can model it when they code the actual product [1].

2. ADVANTAGES OF RAPID PROTOTYPING

Successful realization of product by using of rapid prototyping technology is performed:

- The first pass must be done quickly, and subsequent improvements should be incorporated immediately. While the prototype needs to give customers a realistic feel for the product, it does not need to include special graphics or computational algorithms that require a lot of time and effort to create.
- The prototyped user interface is reviewed, commented upon, improved, and reviewed again in a repeating cycle. No one creates a perfect design the first time.
- Ideally, the prototype should be built by a domain expert. Domain experts are familiar with the user – his or her job, expectations, requirements, jargon, and priorities. These people may have done the user's job in the past. Domain experts can do the best job of incorporating user requirements into the prototype. If your prototyping tool is too difficult for the domain expert to use, make sure that the domain expert works closely with the programmer.

Rapid prototyping has many advantages over the traditional process used to develop a product, including those describe below.

Rapid prototyping encourages creating a detailed design at the beginning of a product's development. This early design work can lead to a more usable product in a shorter period of time. In fact, some studies found that development teams that prototyped produced systems that were easier to learn than development teams that did not prototype. Teams that prototyped got these results using 45% less effort and 40% less code. A complex system can be prototyped successfully for less than 10% of the total software development cost.

Since rapid prototyping produces screens that are easy for your team to review and copy, you can establish screen design conventions. The conventions allow the team to produce screens that are consistent, thereby reducing the amount of code that has to be rewritten during prototyping and coding.

Rapid prototyping allows customers to see and use realistic screens early in product design, when changes can be made quickly and cheaply. You can conduct walkthroughs and usability tests with the prototype, then

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use this customer feedback in revising the prototype to better match customer requirements and preferences. Some studies found that users of a prototyped system evaluated it more favorably and were more satisfied with it than users of the same system developed in the traditional way.

As customers see their design suggestions incorporated quickly into the prototype, they come to think of it as “their” product. Customers can begin to believe that they are designing a product to meet their unique needs, with IBM simply facilitating the process. Customers take pride in the prototype and try to make is as useful as possible. This pride of ownership results in a product that closely matches customer needs.

Seeing is believing. Instead of telling management how many KSLOCs (thousand software lines of code) you’ve finished, management can see your progress as you build and refine the prototype. This visible process builds your credibility and provides a direct, easy-to-understand way to demonstrate progress.

By reviewing your prototype, these team members can get an early understanding of the product’s functions and user interface and can suggest improvements that meet customer needs.

Rapid prototyping allows domain experts, information developers, and usability representatives to become an integral part of the design team. Instead of waiting for the code to be finished, they can work side-by-side with development to produce a user interface (screens, screen flow, help, and documentation) that is simple, consistent, and easy-to-use.

Instead of writing a long and detailed specification that describes the proposed screens and navigation of your product, show the screens and navigation by using the prototype as the product functional specification. Using the prototype will save you significant documentation time and will be a much easier way for people to understand your proposed product [3].

3. PRINCIPLE OF FUSED DEPOSITION MODELING

Fused Deposition Modelling (FDM) was developed by Stratasys in Eden Prairie, Minnesota. In this process, a plastic or wax material is extruded through a nozzle that traces the part's cross sectional geometry layer by layer. The build material is usually supplied in filament form, but some setups utilize plastic pellets fed from a hopper instead. The nozzle contains resistive heaters that keep the plastic at a temperature just above its melting point so that it flows easily through the nozzle and forms the layer. The plastic hardens immediately after flowing from the nozzle and bonds to the layer below. Once a layer is built, the platform lowers, and the extrusion nozzle deposits another layer. The layer thickness and vertical dimensional accuracy is determined by the extruder die diameter, which ranges from 0.013 to 0.005 inches. In the *X-Y* plane, 0.001 inch resolution is achievable. A range of materials are available including ABS, polyamide, polycarbonate, polyethylene, polypropylene, and investment casting wax [4].

For better orientation of user in process of setting of suitable parameters during the preparation of printing there was algorithm elaborated which accumulates all factors and steps that lead to selection of most suitable variant. All the attempts were realized as a part of preparation stage for printing on UPrint machine that utilize FDM technology to build the prototype. This technology, developed by Stratasys, uses the software program to orient the model and generate building slices. Printer dispenses with basic building material and support material which is used if necessary for creation of holes, cavities, drafts, etc. Each material has its own nozzle. Creation of particular prototype layers with use FDM method is shown in Fig. 1.

On the Department of Manufacturing Technologies of the Faculty of Manufacturing Technologies of TU Košice with a seat in Prešov there is UPrint 3D FDM printer from Dimension available. It is a small 3D printer with 635 × 660 × 787 mm dimensions suitable for office environment which uses the printing principle of Fused Deposition Modeling. Maximum dimensions of printed prototype are 203 × 152 × 152 mm. This printer prints only one layer of constant thickness 0.254 mm which is as the accuracy of the print in the Z axis very acceptable [5].

These printer used as building material thermoplastic ABCplus Ivory which comes in standardized packages as fiber with a diameter of 1.6 mm rolled onto a reel. Each spool contains 500 cubic centimeters of material. The support material used is resin Soluble SR-P400 which comes in the same package as a building material. After printing the prototype it is necessary to clean the prototype of the auxiliary material.

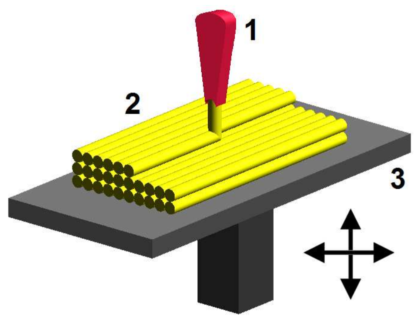

Fig. 1. Application of Fused Deposition Modelling technology.

Fig. 2. FDM device UPrint from Dimension.

For this printer we use Catalyst program which serves to complete printing settings such as disposition of components on working desktop or set-saving modes where savings can be achieved by building and supporting material to 40% depending on the shape and parts at the expense of strength of the prototype. In a first step we generated STL data in the CAD system that can be loaded to the Catalyst program for layered rendering of the model. After starting of print cycle the system warms up printing jet and whole work area for working temperature. This lasts about 15 minutes, during which the nozzle and purifying device are calibrated. Followed by the print itself, the nozzle is moving over X - Y pad and working in the Z axis. After printing it is necessary to separate the support material from the building one. In the semi-simple components the support material can be separated without any problems, as because of reducing temperature it is particularly fragile. However, for complex parts with cavities there is need to use the washer to remove support material from places that are not accessible for any instrument. The last step is gear assembly, which consists of forty parts and testing of prototype functionality. During the functional testing, we used an electric motor with a speed regulator connected to the input shaft. The test showed flawless shifting and fixing of rates in the desired position [7].

4. PROPERTIES OF MATERIALS USED IN FUSED DEPOSITION MODELING

Fused Deposition Modeling is one of the typical RP processes that provide functional prototypes of ABS plastic. FDM produces the highest-quality parts in Acrylonitrile Butadiene Styrene (ABS) which is a common end-use engineering material that allows you to perform functional tests on sample parts. FDM process is a filament based system which feeds the material into the heated extrusion head and extruding molten plastic that hardens layer-by-layer to form a solid part. FDM parts are tougher and more durable than those produced by SLA. ABS parts are sufficiently resistant to heat, chemicals, and moisture that allows FDM parts to be used for limited to extensive functional testing, depending upon the application.

FDM materials allow you to manufacture real parts that are tough enough for prototyping, functional testing, installation, and most importantly — end use. Real production thermoplastics are stable and have no appreciable warpage, shrinkage, or moisture absorption, like the resins (and powders) in competitive processes.
Because thermoplastics are environmentally stable, part accuracy (or tolerance) doesn't change with ambient conditions or time. This enables FDM parts to be among the most dimensionally accurate. Basic FDM materials [8, 9]:

1. ABS - An ABS prototype has up to 80% of the strength of injection moulded ABS meaning that it is extremely suitable for functional applications.
2. ABSi - ABSi is an ABS type with high impact strength. The semi-translucent material used to build the FDM parts is USP Class VI approved.
3. ABS-M30 - ABS-M30 is 25-75% stronger than the standard ABS material and provides realistic functional test results along with smoother parts with finer feature details.
4. ABS-ESD7 - ABS-ESD7 is a durable and electrostatic dissipative material suited for End-use components, Electronic products, Industrial equipment and Jigs and fixtures for assembly of electronic components.
5. PC-ABS - PC-ABS is a blend of polycarbonate and ABS plastic which combines the strength of PC with the flexibility of ABS.
6. PC-ISO - PC-ISO blends are widely used throughout packaging and medical device manufactures. The PC-ISO material used to build the FDM parts is USP Class VI approved and also ISO 10993-1 rated.
7. ULTEM 9085 - ULTEM 9085 is a pioneering thermoplastic that is strong, lightweight and flame retardant (UL 94-V0 rated). The ULTEM 9085 material opens up new opportunities for the direct additive construction of production grade components.

5. DESIGN AND PRODUCTION OF PART REALIZED FROM ABS MATERIAL

To prototype successfully, first select an appropriate rapid prototyping tool. There are hundreds of rapid prototyping tools available. They range from simple graphics packages that allow you to draw screens to complex systems that allow you to create animation. Each tool is better for some functions than for others. Although several rapid prototyping techniques exist, all employ the same basic five-step process. The steps are:

1. Creation of CAD models of the product parts.
2. Conversion of CAD models into STL formats.
3. Use of STL files in Rapid Prototyping devices.
4. Production of the parts by one layer atop another.
5. Cleaning of parts and assembly of the product.

Model of selected part was created and subsequently modified in CAD/CAM/CAE system CATIA V5 R19. Transfer of models between CATIA nd another CA systems was implemented using the exchange format IGES where they were treated. On Fig. 3 is example of CAD model of parts in CATIA.

On the start of the production process are generated STL data in the CATIA system and these STL data are next loaded to the Catalyst program for layered rendering of the model (Fig. 4).

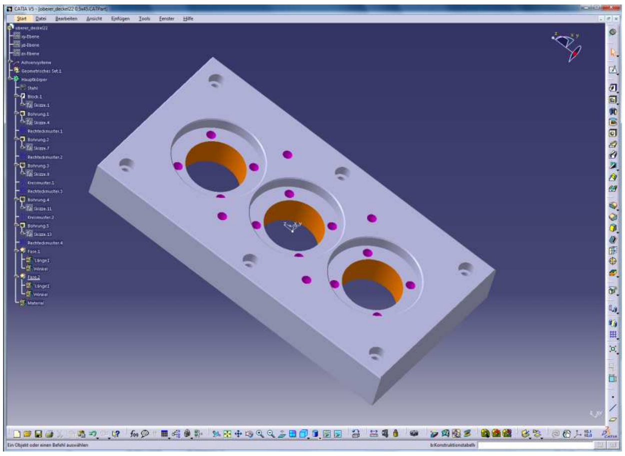

Fig. 3. Model of the part in CATIA system.

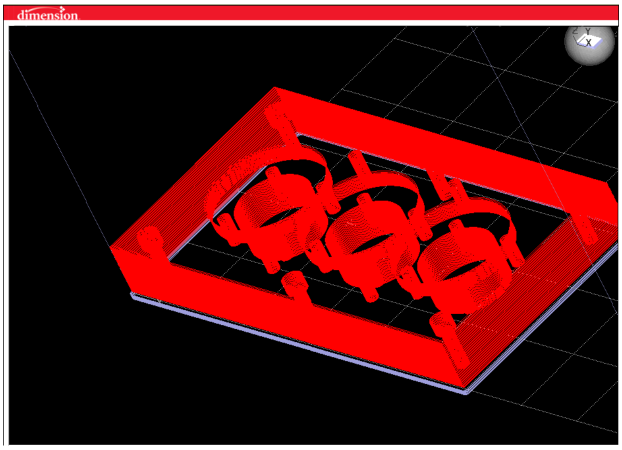

Fig. 4. Layered model of the part in Catalyst software.

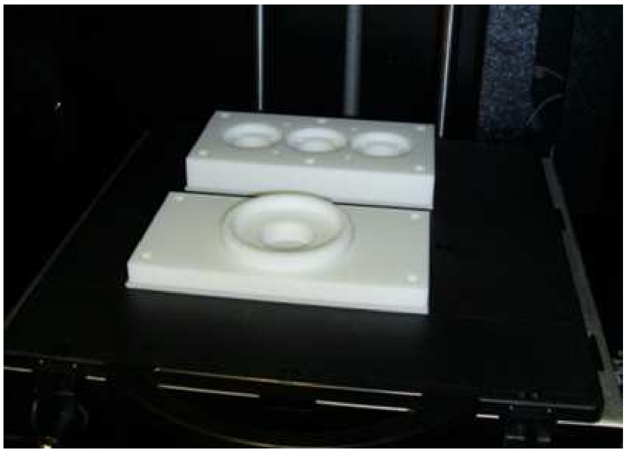

Fig. 5. Printed prototype of 3D part by FDM method.

For RP methods there are specific production devices (3D printers) that use their own software based on principle of reading and processing of input STL data. In spite of different manufacturers, such programs have the same characteristic features:

- settings for single layer resolution,
- settings for density of model material,
- settings for density of support material,
- STL processing to layer mode.

All these software solutions allow their user to change large number of different settings. Changes are made by user himself. Programs for preparation of FDM production make many actions easier and more automatic, but deciding process about particular parameters is still up to user. In case of using the automatic mode these decisions are made by program without explanation, so there is space for optimization of setting contrary to user criteria. Solution could be realized in implementation of deciding steps or automatic decision with actual information about reasons running on background, eventually together with information about parts already produced.

First step is to define the surfaces and constructional points that represent functional features of part and thus they should condition requirements on quality. Considering these surfaces it is necessary to think about number and type of existing reference entities in model that can be used for part orientation. In case that STL data do not have required quality there is need to increase the number of polygons and re-export to STL format (STL editing).After importing of STL file we get to the part orientation. Commonly there is automatic option solved by several software procedures. These steps can be in contrary to user requirements. More effective way would often be manual orientation, where is part position defined by relation of its surface or edge to the working board or to some coordinate axis of used environment. Available are also standard functions like rotation and scaling. With part oriented we can proceed to another settings that include style and density of particular printing layers. Value of minimal thickness of single layer is conditioned by hardware properties of printer or building material. There is parameter usually called Model interior, for setting of quality of basic building material. Among standard options there is Solid mode, advised by manufacturer, as printed material results in one whole. Other possibilities are Sparse-Low density and Sparse-high density. They save basic material by creating the grid of cavities inside the volume. Last mentioned options are applied mainly in huge models without requirement on technical functionality. Walls are partially weakened and have lower strength. Support fill is another parameter that is very similar to the previous one except for it defines the usage of support material. It is often applied for skew surfaces and holes. Common options are Minimum, Basic, Sparse and Surround. For construction reasons it is wise to use Sparse variant to avoid the wall crash because of their small thickness. Surround option on the other hand is used for complicated models. Support material then covers all the model and needs to be removed in special washing device. Models created by using low parameters are sufficient for most common application purposes – for presentations. Higher parameters of quality means longer printing times and higher energy consumption, but utilization possibility of such models is much higher as they can be used instead of real functional parts. Next step in 3D printing preparation process is to define the location of the model on working board of printer. On Fig. 5 is view of workplace of 3D FDM printer UPrint with printed part [4].

6. MAIN PARAMETERS OF RP FDM PROCESS

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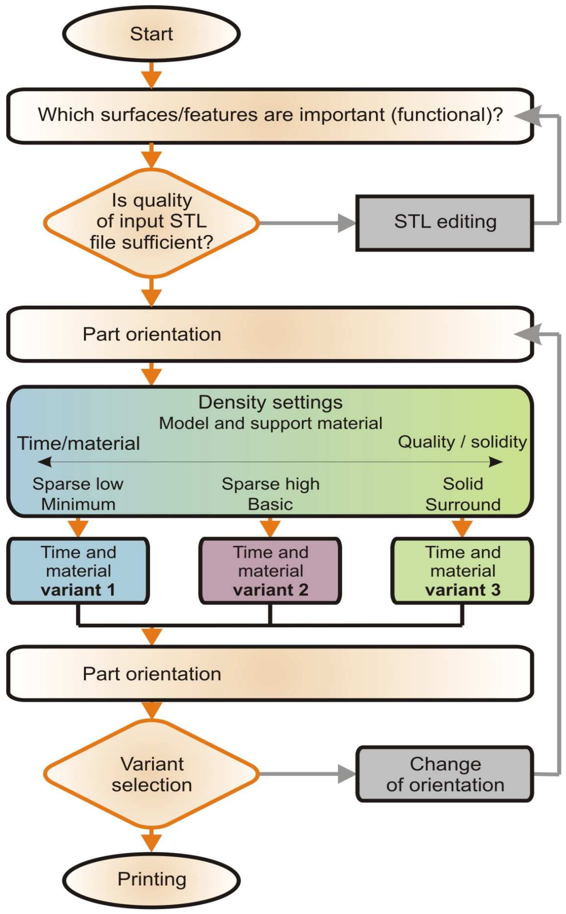

Fig. 6. Algorithm created for RP preparation process.

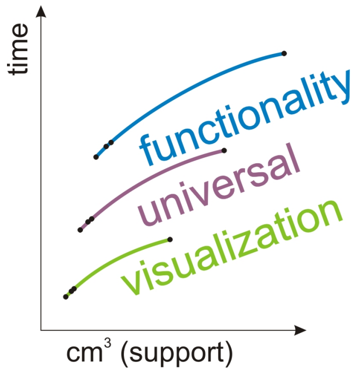

Fig. 7. Dependencies of printing time on used material.

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More effective way would often be manual orientation, where position of part is defined by relation of its surface or edge to the working board or to some coordinate axis of used environment. Available are also standard functions like rotation and scaling. With part oriented we can proceed to another settings that include style and density of particular printing layers. Value of minimal thickness of single layer is conditioned by hardware properties of printer or building material. There is parameter usually called Model interior, for setting of quality of basic building material. Among standard options there is Solid mode, advised by manufacturer, as printed material results in one whole. Other possibilities are Sparse-Low density and Sparse-high density. They save basic material by creating the grid of cavities inside the volume. Last mentioned options are applied mainly in huge models without requirement on technical functionality. Walls are partially weakened and have lower strength. Support fill is another parameter that is very similar to the previous one except for it defines the usage of support material. It is often applied for skew surfaces and holes. Common options are Minimum, Basic, Sparse and Surround. For construction reasons it is wise to use Sparse variant to avoid the wall crash because of their small thickness. Surround option on the other hand is used for complicated models. Support material then covers all the model and needs to be removed in special washing device. Lower settings for density and volume of used basic and support material answer to lower strength and functional properties but at the same time present assumption for lowering the cost of prototype creation. Models created by using low parameters are sufficient for most common application purposes – for presentations. Higher parameters of quality mean longer printing times and higher energy consumption, but utilization possibility of such models is much higher as they can be used instead of real functional parts. Next step in RP preparation process is to define the location of the model on working board of printer. Goal is to optimally place printed model considering possibility of allocation of other prototypes (printed together or later) on the same printing board. After thinking of all mentioned parameters user is supposed to do the decision that should be based on information about printing economy, volumes of both kinds of material and relevant printing times. Good start for making such decision right is to have all information cumulated at one place and thus to have much better idea of expected printing results. In case of interest there is a way to get back to the part orientation step.

Figure 7 is a graphical expression of changes in support material application style based on values from previous tables. Curves describe dependence of printing time on usage level of support material. Areas expressing the character of printing from the viewpoint of its economy are situated between these curves. User can decide for concrete category according to expected or requested application field of printed part.

7. CONCLUSIONS

Rapid prototyping is starting to change the way companies design and build products. On the horizon, though, are several developments that will help to revolutionize manufacturing as we know it.

One such improvement is increased speed. "Rapid" prototyping machines are still slow by some standards. By using faster computers, more complex control systems, and improved materials, RP manufacturers are dramatically reducing build time. For example, Stratasys recently (January 1998) introduced its FDM Quantum machine, which can produce ABS plastic models 2.5–5 times faster than previous FDM machines. Continued reductions in build time will make rapid manufacturing economical for a wider variety of products.

Another future development is improved accuracy and surface finish. Today's commercially available machines are accurate to ~0.08 millimeters in the x-y plane, but less in the z (vertical) direction. Improvements in laser optics and motor control should increase accuracy in all three directions. In addition, RP companies are developing new polymers that will be less prone to curing and temperature-induced warpage.

The introduction of non-polymeric materials, including metals, ceramics, and composites, represents another much anticipated development. These materials would allow RP users to produce functional parts. Today's plastic prototypes work well for visualization and fit tests, but they are often too weak for function testing. More rugged materials would yield prototypes that could be subjected to actual service conditions. In addition, metal and composite materials will greatly expand the range of products that can be made by RM.

Many RP companies and research labs are working to develop new materials. For example, the University of Dayton is working with Helisys to produce ceramic matrix composites by laminated object manufacturing. An Advanced Research Projects Agency / Office of Naval Research sponsored project is investigating ways to make ceramics using fused deposition modeling. As mentioned earlier, Sandia/Stanford's LENS system can create solid metal parts. These three groups are just a few of the many working on new RP materials.

Another important development is increased size capacity. Currently most RP machines are limited to objects 0.125 cubic meters or less. Larger parts must be built in sections and joined by hand. To remedy this situation, several "large prototype" techniques are in the works. The most fully developed is Topographic Shell Fabrication from Formus in San Jose, CA. In this process, a temporary mold is built from layers of silica powder (high quality sand) bound together with paraffin wax. The mold is then used to produce fiberglass, epoxy, foam, or concrete models up to 3.3 m × 2 m × 1.2 m.

At the University of Utah, Professor Charles Thomas is developing systems to cut intricate shapes into 1.2 m × 2.4 m sections of foam or paper. Researchers at Penn State's Applied Research Lab (ARL) are aiming even higher: to directly build large metal parts such as tank turrets using robotically guided lasers. Group leader Henry Watson states that product size is limited only by the size of the robot holding the laser.

All the above improvements will help the rapid prototyping industry continue to grow, both worldwide and at home. The United States currently dominates the field, but Germany, Japan, and Israel are making inroads. In time RP will spread to less technologically developed countries as well. With more people and countries in the field, RP's growth will accelerate further.

One future application is Distance Manufacturing on Demand, a combination of RP and the Internet that will allow designers to remotely submit designs for immediate manufacture. Researchers at UC-Berkeley, among others, are developing such a system. RP enthusiasts believe that RP will even spread to the home, lending new meaning to the term "cottage industry." Three-dimensional home printers may seem far-fetched, but the same could be said for color laser printing just fifteen years ago.

Finally, the rise of rapid prototyping has spurred progress in traditional subtractive methods as well. Advances in computerized path planning, numeric control, and machine dynamics are increasing the speed and accuracy of machining. Modern CNC machining centers can have spindle speeds of up to 100,000 RPM, with correspondingly fast feed rates. Such high material removal rates translate into short build times. For certain applications, particularly metals, machining will continue to be a useful manufacturing process. Rapid prototyping will not make machining obsolete, but rather complement it [6].

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