AC 2007-65: RAPID MANUFACTURING – THE FUTURE OF PRODUCTION SYSTEMS

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Rapid Manufacturing – The Future of Production Systems

ABSTRACT

Rapid Prototyping is a technology that converts three-dimensional computer models into physical parts typically by building layers upon layer of material. This technology has been serving designers for almost 20 years in support of demonstrating, testing, and confirming their designs early and frequently in the product development process. Increasing interest of designers in Rapid Prototyping (RP) in the last decade has led to development of new technologies and advancements in RP materials. Building a functional part or assembly directly from its CAD (Computer Aided Design) model gave manufacturers the opportunity of rapid and custom production capability of parts such as molds, inserts, tools, sub-assemblies and even final products. Hence, the term Rapid Manufacturing (RM) has been added to the terminology. It is unlikely that RM will replace mass-manufacturing techniques in the near future due to some constraints. However, for small lot productions, highly complex parts and increased customization demands by customers – Rapid Manufacturing may be the answer. Today, more than thirty companies around the world manufacture RP systems with different capacities and features. Rapid Prototyping / Manufacturing system producers utilize different technologies that require different materials. In this environment, manufacturing companies experience serious difficulties in search of appropriate materials and corresponding technologies for their use. This paper is aimed to present background on RP/RM technologies, current application fields of RM, comparison of RM with CNC (Computer Numerical Control) technology, and a critical view of most commonly utilized RM methods. Moreover, emphasis on RP/RM education complements the first portion of the paper with inclusion of Robert Morris University Engineering Department efforts to use RP/RM in engineering curriculum and expand technology awareness among current and prospective engineers.

Background

Rapid Prototyping is a fabrication technology that eliminates use of intermediary processes. RP parts are created directly from computer-aided design (CAD) models. Rapid prototyping

systems create parts from bottom-up, typically by building layers upon layer of material. The part is built by addition of layer-by-layer deposition (FDM), selective solidification of resin (SLA), selective sintering of metal, ceramic, or composites (SLS), and selective powder binding (3-dimensional printing). This layer-based manufacturing technique allows realization of complex geometries with high accuracy.

The RP technology has been serving manufacturers for almost 20 years in support of demonstrating, testing, and confirming their designs early and frequently in the product development process. Most likely, at the end of design iteration, a prototype is needed to provide feedback to design engineers. Using a prototype, a product can be better analyzed to identify errors and improve features. Feedback can also be received from prospective clients to aid the decision-making process. Increasing competition among manufacturers in global markets forced manufacturers to introduce new products more often and faster. Without a doubt, CNC based, handcrafted, or molded prototyping is not helpful enough in such business environment. Hence, interest of designers in RP has been increased during the last decade. CAD models can be realized within hours through RP systems. Large aviation and automotive companies were the early adopters of CAD in 1970s¹. Technological advancements and lower costs of personal computers in early 1980s allowed smaller companies to utilize CAD in design iterations. Today, CAD is the medium of designing new products. Since the emerging of state-of-the-art RP technologies in late 1980s², engineers have been able to deliver their designs within a day or two. Any part drawing regardless of its geometric complexity can be fabricated by RP machines without using intermediary tools such as molds or patterns. Development of new technologies and advancements in materials has permitted producing functional parts such as molds, inserts, tools, sub-assemblies, replacement parts, and even end-use products. Consequently, the term Rapid Manufacturing (RM) has been adopted.

Applications of Rapid Manufacturing

Rapid Manufacturing has gained diverse application fields during the last decade; consequently, it might be a feasible manufacturing solution for small lot productions, highly complex parts and increased customization demands from customers³. Availability of the industrial grade materials such as metals, ceramics, plastics, and composites created an

opportunity for many applications in areas like:

- Aerospace

Clients demand aircrafts with different features. In order to meet customer's need, the aviation industry has to manufacture hundreds of parts in low volumes. RM offers the most feasible solution for this demand. NASA has been utilizing RM technologies for several years to produce parts used in Space Shuttles^{4, 5}. Also, Boeing manufactures single-piece production parts such as air ducts for F-18 fighter jets using RM technology⁴ to avoid producing multiple parts for assembly⁶.

- Automotive

The technology is currently used in the product development process to fabricate prototype parts⁵. RM can be employed for short-run and custom production as well. Formula-1 and NASCAR racing cars are benefiting from RM technologies^{2, 4}.

- Biomedical

Rapid Prototyping and Manufacturing technologies are also employed in the Biomedical Bio-Engineering fields. Especially prosthesis, hearing aids^{5, 7} and dental implants tailored to individuals are commonly fabricated by taking advantage of one of the major strengths of RM, ability to generate almost any geometry out of CAD data⁸. RM can also save lives during pre-surgical activities such as pre-operative planning⁹, pre-forming of fixation components, simulation of surgical procedures, and fit evaluation of implants^{5, 7}.

- Consumer Products

RM technology shortens the time required for tooling through Rapid Tooling⁵. The technology is capable of producing high accuracy tools, molds, and inserts 2 to 6 weeks earlier than conventional methods⁵. RM can be used to gain advantage by launching the product weeks earlier than rival launch. Such approach has been performed to manufacture parts that are used in demo products for commercial expositions.

- **Industrial Machinery Manufacturing**

Industrial machinery manufacturing companies can utilize the RM technology to accommodate customized machinery demand. Most customization demand can be resolved by setups or adding more features to the equipment. However, where additional customization is necessary, new tools or parts may be required. RM allows manufactures to be more flexible to meet customer demands. Durden Enterprises, Inc., Atlanta, GA successfully applied RM method for tooling to meet its customer's demand².

- **Nautical**

The majority of the boats regardless of their size and type require customization due to clients' diverse needs and expectations. Rapid Manufacturing can take place in building hundreds of assembly and replacement parts⁴. The Rapid Prototyping and Fabrication Technologies Division of the Naval Undersea Warfare Center Div. (NUWC), Keyport, Washington utilizes RM to produce casting molds to be used in manufacturing of spare parts for the US Navy¹⁰.

CNC versus Rapid Manufacturing

Computer numerical control (CNC) systems have served manufacturing companies for decades. CNC utilizes two or three-dimensional geometry for part/tool manufacturing as rapid manufacturing systems do. CNC has been considered as a Rapid Manufacturing technology among many manufacturing engineers. CNC technology has been the dominant RP/RM technology before the emergence of additive processes. However CNC technology has limitations with respect to geometry, tool wear, and set-up requirements. RP/RM utilize layer-by-layer build technology. CNC shapes parts by the selective removal of material (metal or plastic). Matthew C. Frank points out the difference between two technologies¹¹: "Unlike the existing rapid prototyping methods, CNC machining is a subtractive process; therefore, one can only remove the material around the periphery of a part (visible cross section of the part)." Prominent rapid prototyping experts Terry Wohlers and Todd Grimm compared CNC and RM technologies in terms of their key features¹² in the table below (Table 1).

Table 1 – CNC vs. Rapid Manufacturing

	CNC	RP/RM
Materials	Unlimited	Limited - Plastics, Metals, Ceramics, Composites
Maximum Part Size	Large enough to handle aerospace parts	1500 x 750 x 700 mm*
Part Complexity	Limited	Unlimited
Feature Detail	Pros: Sharp edges, smooth blends, clean chamfers	Pros: Sharp inside corners, deep & narrow channels, tall & thin walls, ribs and posts
Accuracy	0.0005 to 0.005 inches	0.005 to 0.030 inches
Repeatability	High	Low - Results may vary. Temperature, humidity, orientation, placement, etc can affect the result
Surface Finish	Ra 0.5 to 5 microns	Ra 2.5 to 15 microns
Reliability	Moderate to high	Moderate
Staffing	Significant - Machine setup and operation	Minimal - no staff needed during the process
Skilled Labor	Moderate to high	Minimal
Lead time	Moderate	Short to moderate

*Maximum part size for RP was 600 x 900 x 500 mm when the article was published (January 2003)¹². The numbers were changed in order to show today's reality. ProMetal S15 delivers above-mentioned part size.

RP/RM is likely preferable to CNC where parts with complex geometries are required and quality requirement can be met. Today, rapid manufacturing is not a replacement for CNC, instead it is considered as a complementary technology¹³.

Critical View of Rapid Manufacturing Methods

Industry experts have agreed on several obstacles that limit usage of Rapid Manufacturing^{4,5,8,9}. It is unlikely that RM will replace mass-manufacturing techniques in the near future due to the following constraints.

- **Physical limitations**

Today's commercially available RP systems have enough build volume for most of consumer products. The greatest building volume among RM systems is 59x30x28 inch – machine built by ProMetal¹⁴. However, even the biggest build volume is not enough for a quantity of parts used in aerospace, nautical, and automotive industries. Few RM technologies offer variety of materials that can mimic the final product.

- **Cost**

RP systems price tags vary from lower \$25,000 to \$1,000,000. Additional software and post-process equipment purchase may also be necessary. Up to \$10,000 training cost should be added per labor/operator. Average material cost is \$5.00 per in. cu that does not include additional support and post-process material needed in some technologies.

- **Environmental Issues**

Some RM technologies utilize materials that are not disposable⁵. Additional processes may be required to make those materials safe. Some RM systems require dedicated enclosed space.

- **Lack of technology awareness**

Today, the US has 50% share of RP market¹⁵. The rest of the market is shared by mostly Far East and European countries. Even though, the technology has been commercially available for almost twenty years; it has not been utilized by the majority of manufacturers. Few manufacturing companies established their own RP departments. Most RP usage is provided by the service companies, which creates a distance between the technology and the end-user.

- Lack of education

Few universities in the US offer RP classes. Training for these technologies is generally available through RP system manufacturers, which is typically limited only to one type of machine or technology.

- Technology and material diversity

3D Systems Corp. released first commercial rapid prototyping machine in 1988^{2,5}. The company utilized its patented stereolithography technology. Its rival manufacturers had to utilize different technologies. Today, more than 30 RP system manufacturers sell more than 40 types of machines with different technologies. RP machines offer dissimilar capacities, features, and materials. Moreover, most prototyping materials are not commonly known among engineers. That leads to confusion in material and technology selection.

Table 2 - Most common rapid manufacturing technologies

Technology	Manufacturers	Build Capacities	Materials	System prices*
FDM	Stratasys ¹⁶	8"x8"x12" to 16"x14"x12"	ABS, PC, PPSF / PPSU	\$25,000 to \$400,000
SLA	3D Systems, F&S ¹⁷	10"x10"x10" to 59"x29.5"x19.7"	Photopolymers - Epoxy, acrylic	\$200,000 to \$900,000
SLS	3D Systems, EOS ¹⁸ , F&S	10"x10"x8.5" to 28"x15.2"x22.9"	Steel, Aluminum, Titanium, Ceramics	\$200,000 to \$1,000,000
3D Printing	ProMetal ¹⁴	2"x1.5"x2" to 59"x30"x28"	Steel, Aluminum, Titanium, Bronze, Gold, Ceramics	\$100,000 to \$500,000
EBM	Arcam ¹⁹	7.9"x7.9"x7.1"	Steel, Titanium	\$600,000

* Prices given above are approximate and may vary upon system configuration and support/maintenance contracts. Additional discounts may apply for educational institutions.

Technology Abbreviations (used in Table 2)

FDM: Fused Deposition Modeling

SLA: Stereolithography
SLS: Selective Laser Sintering
3D Printing: Three-dimensional printing
EBM: Electron Beam Melting

Material Abbreviations (used in Table 2)

ABS: Acrylonitrile Butadiene Styrene
PC: Polycarbonate
PPSF / PPSU: Polyphenylsulfone

Emphasis on Education

Although there are limitations, RM is mature enough technology for the production applications. RP/RM technologies have sufficient capabilities and features for today's industrial use. Universities can have significant role in increasing technology awareness among manufacturing companies by providing related courses to prospective engineers. Graduates -and even interns- may bring fresh ideas to companies with their technology knowledge and hands-on experience. Additionally, related seminars, workshops, and certificate programs would help companies in adopting these technologies.

Robert Morris University – Engineering Department Current RP education

RP and Reverse Engineering course (ENGR 4801/5810) is offered as an elective to RMU Engineering students. The course delivers extensive knowledge of rapid prototyping technologies as well as hands-on training using stereolithography process and reverse engineering tools for industrial applications.

Students are expected to learn the basic concepts and science behind the additive rapid prototyping technologies including stereolithography (SLA), Fused Deposition Modeling (FDM), 3D printing, and Selective Laser Sintering (SLS). They also are expected to understand the technology components such as software and hardware structure and their operation. In the process, they acquire the required skills to be modern, technology savvy engineers.

Students use RP and Reverse Engineering Laboratory that houses the 3D Systems Viper stereolithography (SLA) machine and its post-processing equipment, Minolta Vivid 910 three-dimensional scanner, Mitutoyo Bright-A504 Coordinate Measuring Machine and several workstations with various software programs.

Figure 1: Rapid Prototyping and Reverse Engineering Laboratory Equipment

After going through lectures and tutorials, each student is expected to complete a set of experiments to acquire an understanding of the Rapid Prototyping process. They utilize SLA equipment, the 3D Systems Lightyear software, and 3D Systems Buildstation software. 3D Lightyear is used in preparation of the machine code (.bff file) to be loaded and controlled by the Buildstation software in Viper Machine. Students are also expected to utilize the post processing equipment as well as design software (such as AutoCAD, SolidWorks, or Mastercam) to create digital model of the product they are developing and generate the stereolithography (.stl) file.

Previous ENGR 4801/5810 projects examples include:

- Chess Pawn (Set) Development
- Further Development of a Commercial Construction Toy
- Motorbike Parts Development (Figure 2)
- Stirling Engine Development
- Vice assembly, game pieces for a board game etc. (Figure 3)

Figure 2: Motorbike part development - RP was utilized for both prototyping and tooling

Current student projects include:

- Toy Development
- SME's Rapid Manufacturing (Direct Digital Manufacturing) Competition²⁰. A group of students is developing a computer peripheral device to be manufactured by RM. They will present their functional design at the SME's 2007 Rapid Conference in Detroit, MI.
- NISH (National Institute Severely Handicapped) Workplace Technology Competition²¹. A group of students is developing a mechanism to allow handicapped people to be successful at their workplace. A functional prototype needs to be developed by RMU students to successfully demonstrate their concept.

In addition to the above-mentioned laboratory activities, Tool Development through Secondary Processing (From SLA patterns to Rubber Powder Metal Tooling) will be performed by students during the Spring 2007 term.

Figure 3: Student project parts made with Rapid Prototyping

Students will use SLA parts as patterns in fabrication of shell molds out of rubber latex. These shell molds will be used in turn to make powder metal parts in a cold isostatic press.

In addition to the RNGR 4801/5810 RMU Engineering Department also offers several other classes that employ rapid prototyping such as Product & Tool Design, Integrated Engineering Design, and Engineering Graphics.

RMU – Center for Applied Research in Engineering & Science (CARES)

RMU CARES was formed in 2004 to serve as a link between University and business community. The objective of the CARES is to provide technical and consulting services to local area industries. The center also presents a state-of-the-art environment for RMU engineering students where gaining hands-on experience is possible by working on real life projects under the supervision of experienced faculty. CARES provides also training and presentations of new technologies like robotics, rapid prototyping and process automation. CARES offers Rapid Prototyping/Manufacturing workshops and seminars to introduce the technology to local manufacturing companies. Attendees gain extensive knowledge of Rapid Prototyping/Manufacturing technologies including material and technology selection in terms of advantages, limitations, and current industrial applications. Attendees are invited on annual basis to update their technology knowledge.

Conclusions and Future Work

RP/RM is one of the fastest growing fields in Manufacturing. The RP/RM education at RMU is very effective, enhancing a healthy combination of theory and practice. A successful student completing the ENGR 4801/5810 course gains invaluable information on these technologies, and is able to operate all related hardware and software tools that include SLA technology, Reverse Engineering tools, and CNC technology. This knowledge and skill set is then applied in his/her CARES Research or Engineering Projects or Integrated Engineering Design assignment (Capstone Course Project). Being competent in these areas make the student employable by CARES during his/her education and by the local industry. Students' response and feedback on these courses show their satisfaction in the learning process. It is not uncommon to see a senior student running the RP machine or a CNC a couple days before their graduation since he/she wants to gain more experience.

In the near future RMU - School of Engineering, Mathematics, and Science plans to expand Rapid Prototyping & Manufacturing capabilities by adding several other technologies to its inventory. Students will have more hands-on-experience with diverse RP/RM technologies, such as Desktop Composite Printing, 3D Metal Printing, and possibly Rapid Mold Fabrication.

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