Rapid Prototyping: State of the Art

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This report provides an overview of the current applications and technologies associated with rapid prototyping. It expands upon previous MTIAC reports on this topic and describes the status of equipment suppliers in terms of technical advancements, market size and share, existing and potential applications for rapid manufacturing, and the implications of this technology for the DoD.

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EXECUTIVE SUMMARY

Rapid prototyping is an extremely important technology to both the commercial sector and the Department of Defense. It is quickly becoming a mainstream technology for the production of models to evaluate fit and form or tooling for low volume manufacturing. Much less mature, but emerging, is the application of rapid prototyping to the direct manufacture of replacement, refurbished, prototype, or low volume production functional plastic and metal parts with acceptable in-service performance, life, and reliability.

There are five categories of rapid prototyping technologies, as listed below.

- Stereolithography or other Photopolymer Based
- Laser Sintering or Net Shaping
- Fused Deposition
- Inkjet and 3D Printing
- Lamination

Stereolithography was the first type of rapid prototyping technology to be introduced commercially and it continues to enjoy success worldwide, due partly to the maturity of the machine and materials technology. Most currently installed equipment is based on this technology. The core of the rapid prototyping market is comprised of 26 machine manufacturers, several material suppliers, and an estimated 40 major service providers worldwide. Further, there are nearly twenty companies emerging as potential suppliers of RP equipment. Since 1987, the year stereolithography was first introduced, the U.S. has dominated the market. However, China and Japan are beginning to make significant inroads in this field. Other countries with RP producers include Germany, Sweden, and Singapore.

Through the end of the year 2001, 81.3% of all machines sold came from U.S. manufacturers. The leading U.S. producers of rapid prototyping machines include 3-D Systems, Cubic Technologies, Optomec, The POM Group, ProMetal, Sanders Design International, Solidica, Stratasys, and Z Corporation. Leading European companies in the field of RP include two Swedish companies, Arcam and Speed Part; and four German companies Envision Technologies, EOS, F&S, and Generis. There are several companies in Japan that have commercialized machines for rapid prototyping including Autostrade, CMET, Denken Engineering, Kira, Meiko, Sony/C-Mec, Toyoda Machine Works, and Unirapid.

The primary applications for Rapid Prototyping are in the development of functional models; fit/assembly models and prototype parts; creating patterns for prototype tooling and metal castings; and in creating visual aids to support engineering and tool making. However, the breadth of applications for RP technology is ever widening, moving beyond metal and plastic parts and now includes jewelry, paper items, and medical products.

Other key trends in the RP industry are to lower price machines and applications requiring more precision than seen from earlier systems.

The technology is moving beyond prototyping to the manufacture of final parts (rapid manufacturing), and also expanding to rapid tooling, for which there are over 20 techniques presently being developed. Laser additive manufacturing, computer-aided manufacturing of laminated engineering material, electrochemical fabrication, direct fabrication, rapid micro product development, a specific surface process, and direct photo shaping are among the more prominent developments. Since 1999, over 450 patents have been issued that are related to Rapid Prototyping. Material development is serving as an enabling technology for the advancement of the utilization of rapid prototyping, especially in polycarbonates, thermoplastics, and liquid photo curable resins.

Regardless of the industry dynamics of new companies forming and others going out of business or merging, the overall number of companies, machine types available, and applications of RP technology continue to grow. What doesn't seem to be changing is that universities and/or Governments, both in the U.S. and abroad, seem to be the foundation for major technical R&D and technical innovations.

The impact of RP to the production and maintenance of weapon systems is profound and includes financial, technical, and logistical advantages. More specifically, these include cost savings, reduced lead-time, improved sustainment, increased combat readiness, personnel reduction, improved quality, and the opportunity to add new capabilities.

- CONTENTS

LIST OF FIGURES AND TABLES

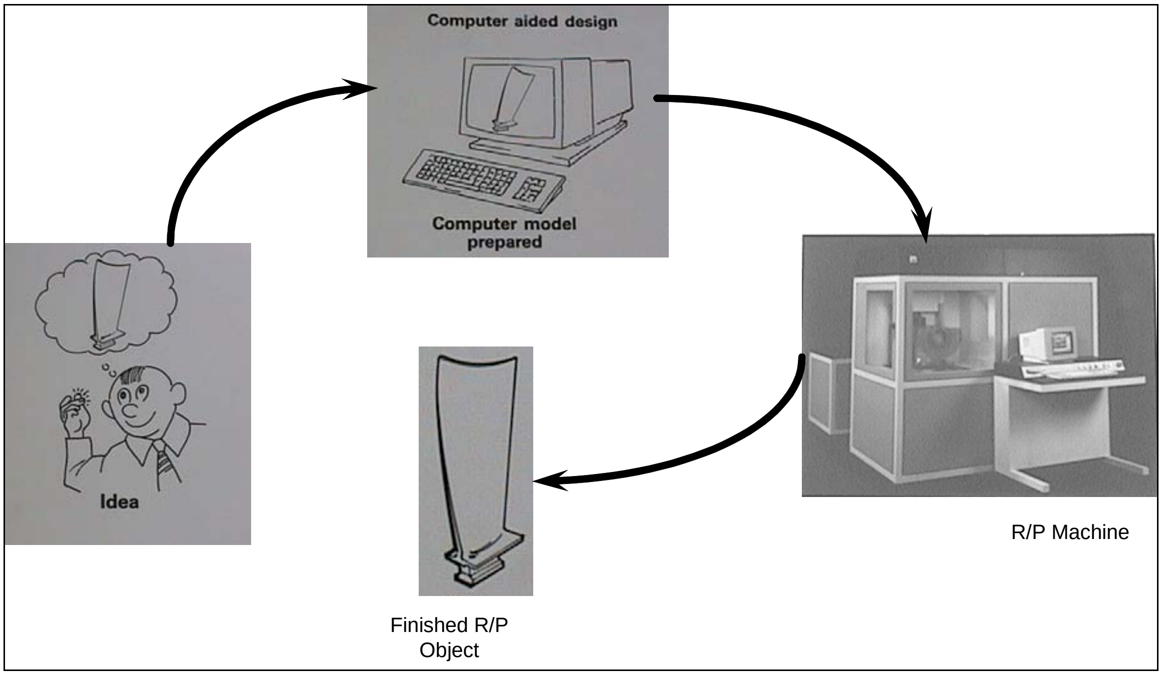
Acronyms:

3D	Three Dimensional
CAD	Computer Aided Design
CAM-LEM	Computer-Aided Manufacturing of Laminated Engineering Materials
CT	Computer Tomography
DLA	Defense Logistics Agency
DLP	Digital Light Processing
DMD	Direct Metal Deposition
D-MEC	Design Model Engineering Center
DMLS	Direct Metal Laser Sintering
DOD	Department of Defense
EBM	Electron Beam Melting
EDM	Electrical Discharge Machining
EFAB	Electrochemical Fabrication
FDM	Fused Deposition Modeling
FFF	Free Form Fabrication
GARPA	Global Alliance of Rapid Prototyping Associations
HIP	Hot Isostatic Pressing
LAM	Laser Additive Manufacturing
LENS	Laser Engineered Net Shaping
LOM	Laminated Object Manufacturing
M^3D	Maskless Mesoscale Material Deposition
MEM	Melted Extrusion Manufacturing
MICE	Mesoscopic Integrated Conformal Electronics
MIT	Massachusetts Institute of Technology
MJM	Multi-Jet Modeling
MPH	Mobile Parts Hospital
MRI	Magnetic Resonance Imaging
QPL	Qualification Product
QPM	Qualification Process/Material
RP	Rapid Prototyping
SCS	Solid Creation System
SLM	Selective Laser Melting
SLP	Solid Laser diode Plotter
SLS	Selective Laser Sintering
SOAR	State of the Art Review
TDP	Technical Data Package

1.0 Introduction

1.1 Rapid Prototyping

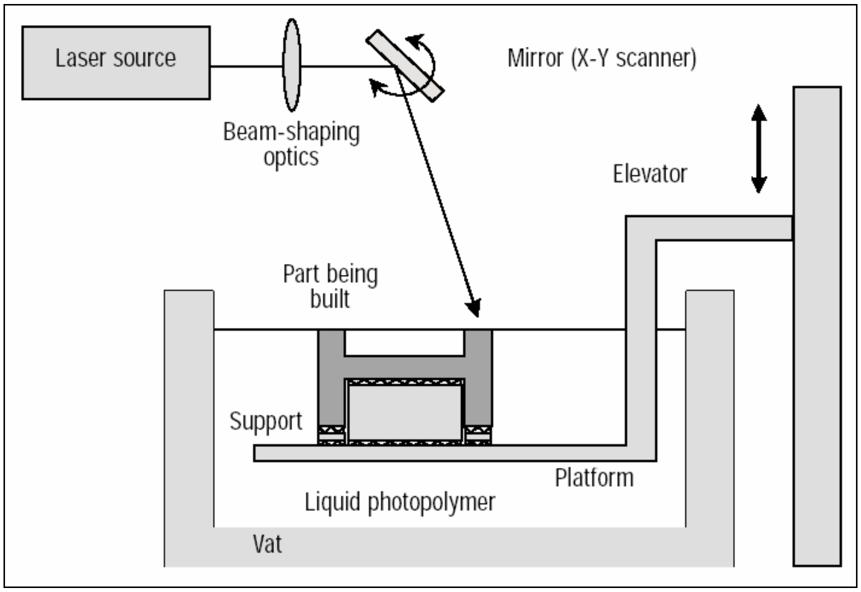
Rapid prototyping (RP) is a relatively new class of technology that includes processes such as stereolithography, fused deposition modeling, laser sintering, and 3D inkjet printing. RP systems produce models, prototype parts, and tooling components from 3D computer-aided design (CAD) model data; Computer Tomography (CT) and Magnetic Resonance Imaging (MRI) scan data; and data created from 3D digitizing systems. Using an additive approach to building shapes, RP systems join liquid, powder, or sheet materials to form physical objects. Layer by layer, RP machines fabricate plastic, wood, ceramic, metal, and composite parts using thin, horizontal cross sections from the 3D computer model. The general process flow used is shown in Figure 1.



Source: National Center for Manufacturing Sciences

Figure 1. Rapid Prototyping Process Flow

An example of one type of rapid prototyping, stereolithography, is shown in Figure 2. The process begins with a vat of photocurable resin. The part is sequentially built layer by layer as it is incrementally lowered while setting on an elevator table. The laser is computer driven by a CAD generated solid model converted to an .stl file representing cross-sectional slices of the solid model. As each layer is photocured by the moving laser, the elevator table drops enough to cover the surface with a new layer of resin. A wiper is used to level the resin between cycles and control the thickness and uniformity. The process continues until the part is complete. To accelerate part generation, each layer is only partially cured during processing and the final part post cured by exposure to higher dosage ultraviolet (UV) light or heat. A number of variants of this general process exist. Key advantages of this process are its low cost and high level of maturity. A very large part can be produced through joining of small sections as shown in Figure 3.



Source: Journal Manufacturing Systems, v19, N1, 2000

Figure 2. Stereolithography Process.

Source: National Center for Manufacturing Sciences

Figure 3. Example of a Large Part Produced by Stereolithography

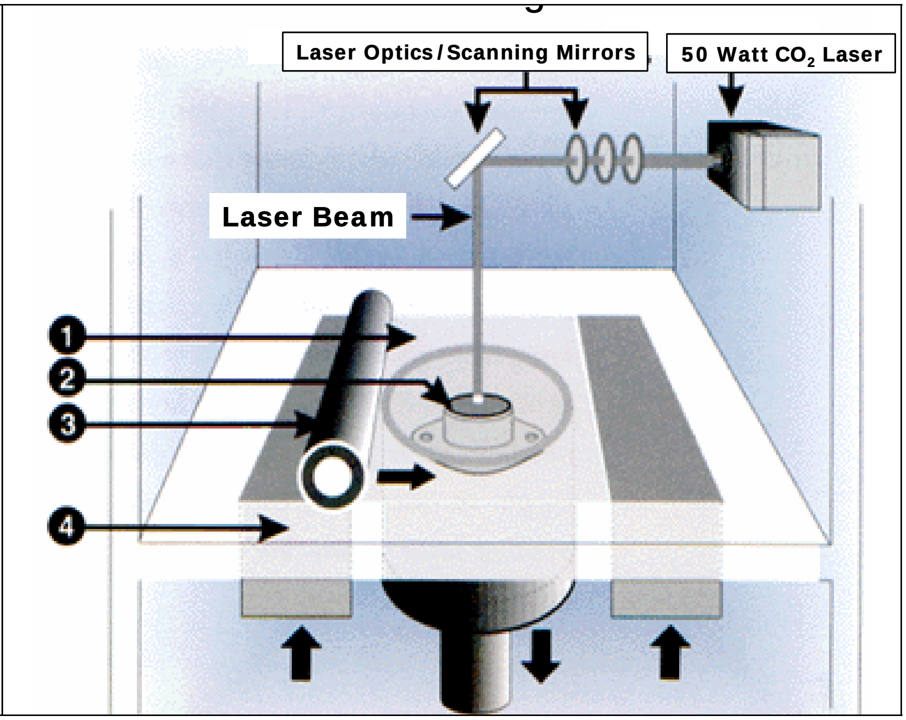
A second example, laser sintering, is shown in Figure 4. With this process, powder replaces the photocure resin. The general process is similar except that the laser is now used to fuse or melt the powder as it translates across the surface. The powder is provided from a second reservoir adjacent to the part containing reservoir. As the elevator table containing the powder moves upward, the part containing elevator moves downward and the powder is swept across the surface of the two reservoirs with excess powder deposited in a third reservoir. Post processing varies with the desired application and ranges from additional heat-treating to infiltration with a lower temperature second phase, e.g., bronze in steel. Key advantages of this process include the ability to directly manufacture functional plastic and metal parts with no additional processing and the wide range of materials than can be considered.

1. A very thin layer of heat-fusible powder is deposited on top of the build cylinder

2. Laser consolidates a cross section that matches the corresponding layer in the .STL file , bonding the particles and fusing the adjoining layers

3. The support platform moves the part downward and the roller mechanism deposits another layer of powder

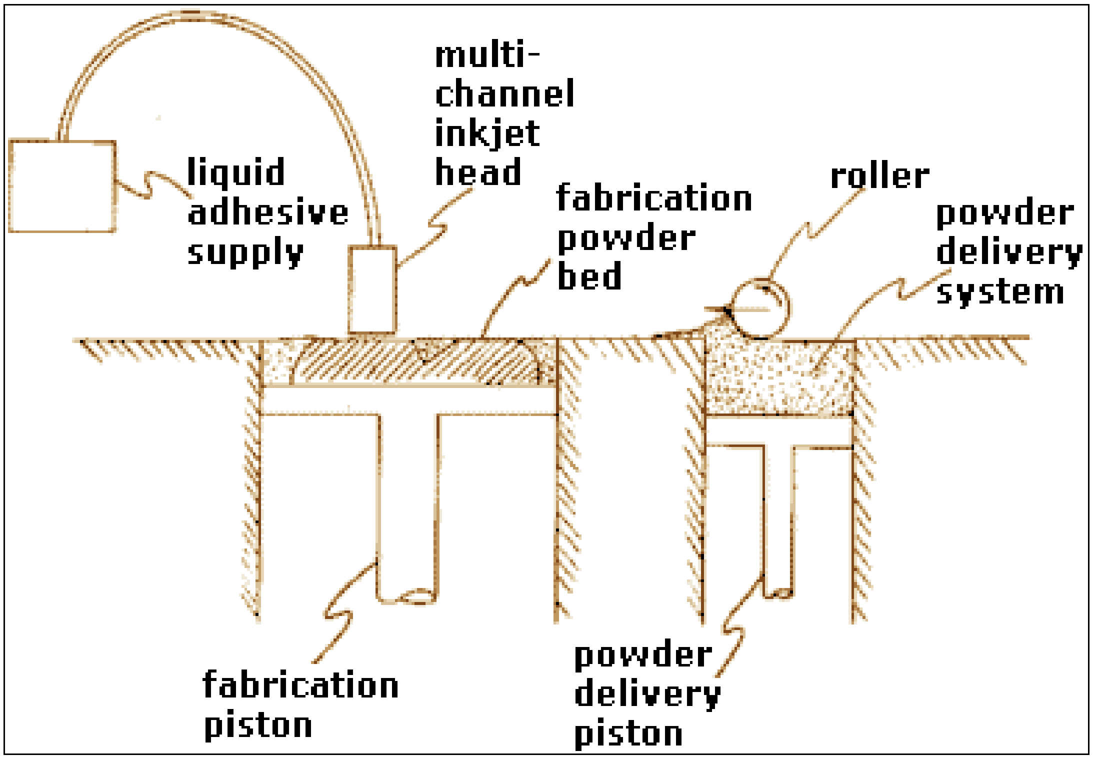
4. The process repeats itself one layer at a time, until the part is fully formed.



Source: Navy Surface Warfare Center, Newport

Figure 4. Selective Laser Sintering Process.

A final example, inkjet printing, is shown in Figure 5. Unlike the previous examples, the laser is replaced with an inkjet head that deposits a liquid adhesive onto the powder as it translates across the surface. Key advantages of this process are the potential for increased productivity through the application of multiple inkjet heads and the ability to spatially introduce a second phase directly as part of the liquid adhesive.

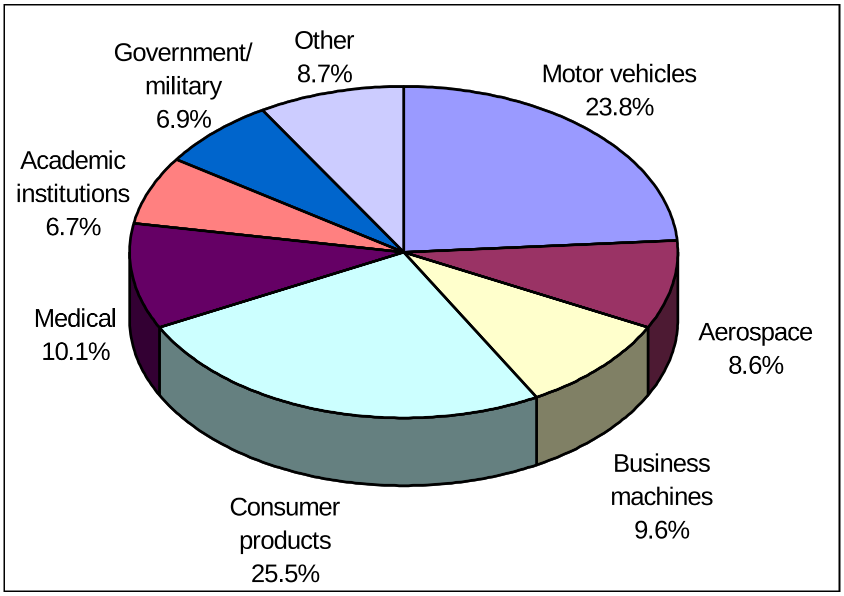


Source: Rapid Prototyping Principles and Applications in Manufacturing by Chua, C.K., et. al.

Figure 5. 3D Printing Process.

1.2 Industries Being Served

Companies that use rapid prototyping cut across most manufacturing industries. Figure 6 shows that of eight key segments, consumer products represent nearly 26%, followed by motor vehicles that represents nearly 24%. The remaining 50% is comprised of medical, aerospace, business machines, academic institutions, medical, and nearly 7% is attributed to the Government/military sector.

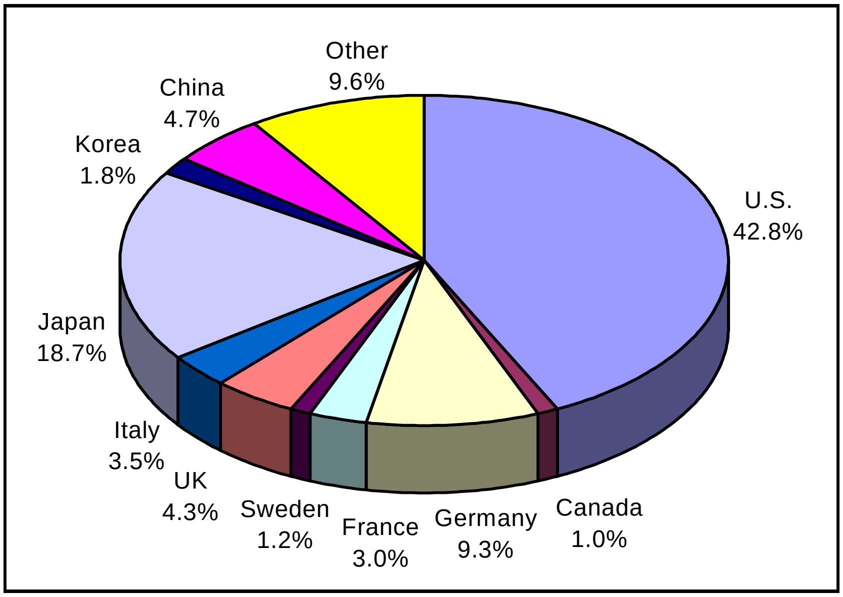


Source: Wohlers Report 2002

Figure 6. Industrial Sectors Where RP Systems are Used

1.3 Installations by Country

The following chart, Figure 7, illustrates system purchases and installations by country for the year 2001. As with system production and sales, the U.S. has the highest percentage, by far, of system installations, followed by Japan, Germany, and China.

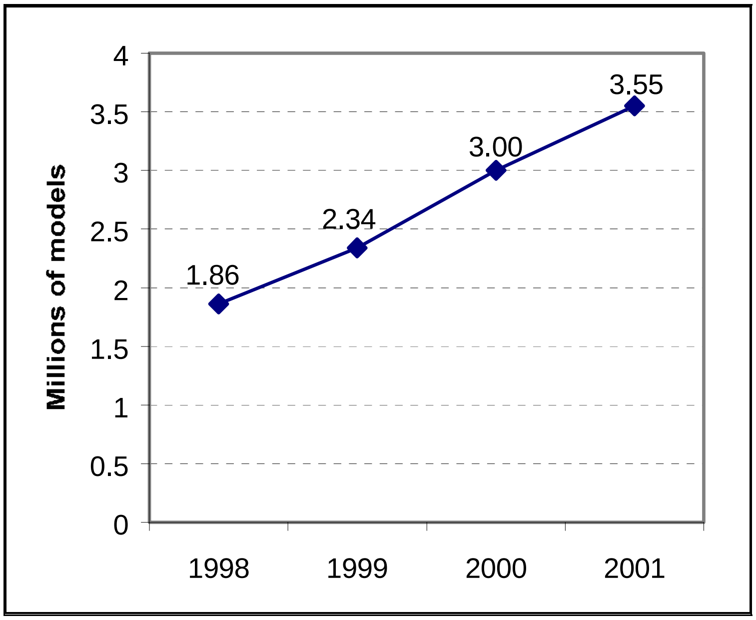


Source: Wohlers Report 2002

Figure 7. Purchases and Installations of RP Systems by Country

1.4 Number of Models Being Produced

Despite a decline in overall industry growth, RP users worldwide produced an estimated 3.55 million models and prototype parts in 2001. This is an increase of 18.3% from the 3 million models produced in 2000. An estimated 2.34 million and 1.86 million parts were produced in 1999 and 1998, respectively.



Source: Wohlers Report 2002

Figure 8. Number of RP Models Produced

1.5 Rapid Tooling

Methods, processes, and systems are also developing for Rapid Tooling (RT). As an emerging technology, the definition of RT is often debated and not clearly defined. Most would agree, however, that RT is driven from a freeform fabrication (FFF) process that is the key to making it rapid.

The demand for faster and less expensive tooling solutions has resulted in more than 20 methods of rapid tooling being developed worldwide. Many companies are pursuing the development and commercialization of RT because of its market potential. In 2001, the secondary RP market segment, which includes tooling created directly from RP processes, was an estimated $385.7 million.

There are also several companies developing RT methods for in-house use with no intention of licensing the technology or making it commercially available. These efforts seek an approach that will offer a strategic advantage over the competition.

1.6 Rapid Manufacturing

RP technology is having a profound impact on the way companies produce models, prototype parts, and tooling. This impact is also being realized in production, as several companies are now using it to produce final manufactured parts. This practice, termed rapid or additive manufacturing (RM), is developing into an intriguing market opportunity. RM may even become the most significant area of growth in this decade.

Among the organizations that are actively applying RM are Align Technology, Bell Helicopter Textron, Boeing and its Rocketdyne division, Cynovad, Interpore Cross International, Jordan-Honda Formula 1 race team, Phonak Hearing Systems, Siemens Hearing Instruments, and the U.S. Navy.

1.7 Commercially Available Technology

A summary of commercially available technologies, equipment suppliers, and materials is shown in Table I. A number of additional technologies are under development or have been developed for captive use for specific proprietary applications and are not commercially available. Equipment available can be placed in one of five categories:

- Laser sintering or net shaping,
- Stereolithography or other photopolymer based,
- Fused deposition,
- Inkjet or 3D printing, and
- Lamination.

Materials available for use with commercial equipment range from paper and polymers commonly used to evaluate fit and form, to metals, which are rapidly evolving from exclusive use in tooling to low volume production of functional parts. Table I illustrates that with the exception of fused deposition, a number of equipment suppliers exist globally for each of the technologies.

Table I. Summary of Technology, Equipment Suppliers, and Materials

Families	Equipment Manufacturers	Materials Available
Laser Sintering or Net Shaping	3D Systems (Formerly DTM) Optomec Aeromet POM Group Arcam EOS GmbH F&S GmbH Speed Part	316, 304 Stainless Steel H13 Tool Steel CP Ti, Ti-6Al-4V Titanium Tungsten Copper Aluminum Nickel Alumindes Superalloys Low Alloy Steel Polystyrene Polycarbonate Polyamide Glass filled Polyamide Bronze Sand
Stereolithography or other Photopolymer Based	3D Systems Envision Technologies Autostrade CMET Inc. Denken Sony/D-MEC Unirapid Wuhan Binhu Mechanical & Electrical Company Shanghai Union Technology	Acrylic Photopolymer Epoxy Photopolymer Vinyl Ether Photopolymer
Fused Deposition	Stratasys Kynergy	ABS Polycarbonate Polyphenylsulfone Polyester
Inkjet or 3D Printing	Multi-Jet Modeling 3D Systems Extrude Hone Solidscape Sanders Design International Z Corporation Generis GmbH Objet	316L Stainless Steel + Bronze 420 Stainless Steel + Bronze Wax Starch Plaster Molding Sand
Lamination	Cubic Technologies (Formerly Helisys) Solidica Toyoda Motor Works Kira Wuhan Binhu Mechanical & Electrical Company Kinergy Solidimension	Aluminum Paper PVC ABS Polycarbonate Polyester Misc Ceramics Misc Metals

1.8 Impact of Rapid Prototyping Technology to the U.S. Department of Defense

The impact of rapid prototyping technology to the production and maintenance of weapon systems is profound and includes both financial, technical, and logistical advantages as described below.

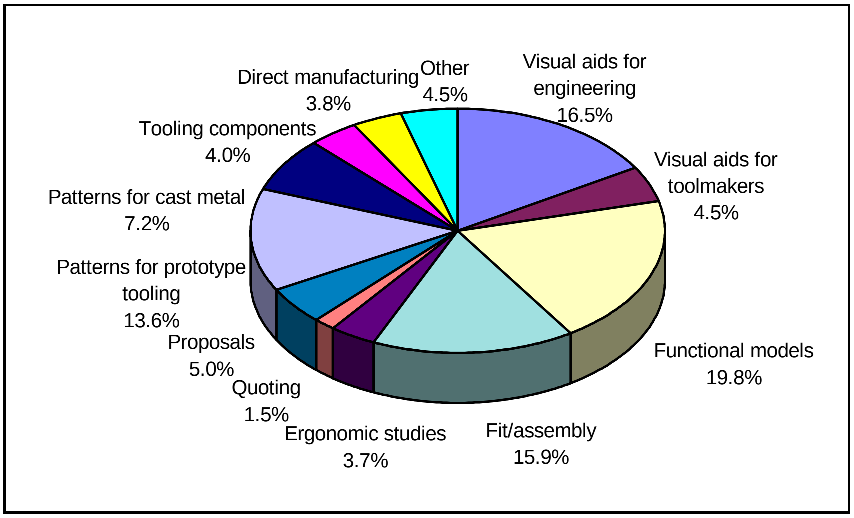
- **Cost Savings**: Rapid prototyping offers DoD a tremendous opportunity to lower the cost of designing, developing, producing, and maintaining weapon systems and their related components. Specific opportunities for cost reduction include, reduced cost of inventories (estimated to be $55 billion); lower manufacturing process costs, especially for hard to machine materials; and the ability to repair versus replace high value parts. Cost savings can be achieved for producing parts with RP that are independent of lot size, especially for DOD low quantity purchases. In many cases, reductions in cost and cycle time can be greater than 50%. Recent qualification of a titanium RP process is expected to result in a $50 million cost savings for application to several F/A 18 fighter components.
- **Reduced Lead Time**: Rapid prototyping technology can reduce production lead time from months to days and is especially suited for low rate production, hard to obtain parts, design prototypes, and castings and forgings requiring long lead tooling and molds. Motorola has reported cycle time reductions of 10X, production tooling costs reduced by an estimated $2 million, and significant improvements in the interaction among product teams.
- **Improved Sustainment**: Legacy systems, including both weapon platforms and logistic support systems, are expected to be in-service by as much as 25 years or more beyond the design life and in some cases, 50 or more years. Production base consolidation, transformation, changes in prioritization, and solvency have generated instability in part supplies. Limited availability of technical data packages requires the use of reverse engineering that is facilitated by rapid prototyping technology.
- **Increased Combat Readiness:** Potentially, mobile manufacturing platforms provide the capability to enhance field level maintenance. Confidence in part delivery is increased and vulnerability is reduced through distributed, local manufacturing. The digital exchange of data accelerates the maintenance process and establishes chronology of repair. There is also the potential for supporting Allied hardware in the field.
- **Personnel Reduction:** Unattended operation, the ability to provide a fully integrated digital manufacturing solution, and a reduced number of conventional manufacturing processes are achievable through rapid prototyping. There are over one million government personnel in logistics support today.
- **Improved Quality:** Rapid prototyping improves manufacturing quality through fewer manual processes and localized heating during repair limits part damage.
- **New Capability:** Sensor integration, graded structures, electronics, new alloys, and heterogeneous structures are some of the potential benefits of RP.

As discussed in Section 8 of this report, key barriers remaining for the acceptance and transition of RP technology within DOD for the application to functional parts includes the lack of technology maturity, the cost of part qualification, and limitations on part size and composition.

2.0 Applications

2.1 How Rapid Prototyping (RP) Models Are Used

As illustrated in Figure 9, the primary applications for Rapid Prototyping are in the development of functional models, fit/assembly models and prototype parts, creating patterns for prototype tooling and metal casting, and in creating visual aids to support engineering and tool making. Combined, the "fit/assembly" and "functional models" segments account for nearly 36% of all RP models. More than 27% use RP as visual aids for engineering, tool making, quote requests, and proposals, and nearly 25% of RP models are being used as patterns for prototype tooling and metal casting, as well as for tooling inserts.



Source: Wohlers Report 2002

Figure 9. Application of Rapid Prototyping Systems

2.2 Form, Fit, And Function

As indicated by the previous chart, a high percentage of RP models are being used for form, fit, and function applications. Engineering groups use RP models for design reviews as well as for seeking input from others when design changes are being considered. RP models and prototype parts are also useful when it is possible to fit them to mating parts to check for proper assembly and potential interference with other parts. Users of RP especially appreciate materials that can withstand the vigor of functional testing. Not all RP materials are up to the task, although a growing number of them are strong enough for some testing applications.

2.3 Pattern-Based Tooling

In the past, a major obstacle to pattern-based tooling was the efficient production of the pattern. RP processes such as stereolithography from 3D Systems and PolyJet from Objet Geometries have all but eliminated the problem. A popular approach is to produce and finish an RP pattern and then use it to produce a silicone rubber mold. Companies are able to cast urethane parts in the molds—parts that mimic the physical and aesthetic properties of injection molded thermoplastics. Companies also use RP patterns to aid them in the creation of epoxy-based composite tooling, spray metal tooling, rubber/plaster tooling, and other methods of tooling.

2.4 Rapid Tooling

Several companies are developing methods and machines that promise to speed the tool-making process. Other potential benefits include reduced tooling costs and higher performing tools. In part, performance gains come from producing cooling channels that conform to the shape of the mold or die cavity, thus improving production cycle time. Other methods reduce or eliminate the need for EDM (spark erosion), saving significant time and expense.

Encouraging progress from the recent past include machines, processes, and companies such as Direct Metal Deposition (DMD) from The POM Group, Direct Metal Laser Sintering (DMLS) from EOS, Electron Beam Melting (EBM) from Arcam, Laser Engineered Net Shaping (LENS) from Optomec, M3 Linear from Concept Laser GmbH, ProMetal from Extrude Hone, RSP Tooling from RSP Tooling LLC, Sprayform tooling from Ford, SLS tooling from 3D Systems, and Ultrasonic Consolidation from Solidica.

2.5 Investment Casting

Several RP processes are capable of making patterns that are used to produce ceramic investment casting shells. Among them are the stereolithography, laser sintering, and ThermoJet machines from 3D Systems, ModelMaker II and PatternMaster from SolidScape, and laser sintering from EOS. In each case, the RP pattern replaces the conventional wax pattern used in the process of making an investment casting shell. One of the most mature RP methods is QuickCast from 3D Systems. A stereolithography machine is used to produce a mostly hollow pattern in photopolymer that is subsequently coated, repeatedly, in ceramic to produce the shell.

2.6 Short Run Production and Custom Manufacturing

An exciting application is the use of RP to produce final production parts. The cost to produce a single RP part is usually inexpensive compared to conventional methods of manufacturing. The technology, therefore, lends itself to custom manufacturing and even mass customization. A pioneer in this area is Boeing. The company is producing several parts, such as cooling ducts, for the space shuttle fleet, the international space station, and F18 fighter jets.

Another company breaking new ground is 3T RPD of England. The RP service provider is using laser sintering to manufacture many different parts of Jordan-Honda's Formula 1 racecars. Parts include cooling ducts, electrical boxes, and panels that form the aerodynamic skin on the cars. The company is producing an average of about 35 parts per week and the turn-around time is usually about 2 days.

Medical technology is another innovative application of RP technology Align Technology has invented the Invisalign process that replaces conventional metal and wire braces for teeth. It involves the production of 12-48 clear plastic aligners that incrementally straighten crooked teeth. Hearing aid companies, including Phonak Hearing Systems and Siemens Hearing Instruments, are using RP technology to manufacture thousands of custom-fit in-the-ear hearing aid shells.

3.0 Machines from the U.S.

Many systems for rapid prototyping have developed since 1987, the year that stereolithography was first introduced. The majority of the systems sold have been from U.S. manufacturers, although a growing number are coming from producers in both Europe and Asia. Through the end of the year 2001, 81.3% of all machines sold came from U.S. manufacturers.

Stereolithography continues to enjoy success worldwide, due partly to the maturity of the machine and materials technology. While stereolithography has been the favorite process in Japan, the U. S. has been developing a mix of technologies such as laser sintering from 3D Systems and EOS, fused deposition modeling from Stratasys, and 3D inkjet printing from Z Corporation, which have established themselves and surpassed stereolithography for specific applications.

The core of the Rapid Prototyping market is comprised of 26 machine manufacturers, several material suppliers, and an estimated 40 service providers worldwide. The leading U.S. producers of rapid prototyping machines includes 3-D Systems, Cubic Technologies, Optomec, The POM Group, ProMetal, Sanders Design International, Solidica, Stratasys, and Z Corporation. The following provides a discussion of these companies.

3.1 3D Systems

3D Systems currently dominates the RP market. In 2001, the company's market share was 22.5% for all RP products and services sold worldwide. The 3D Systems Company was founded in 1986 by Charles Hull, a pioneer in the technology of stereolithography. The company is publicly traded and listed on the NASDAQ as TDSCE. Annual sales are estimated at $121 million. 3D Systems offers RP products and services the four technical areas of stereolithography, selective laser sintering, multi-jet modeling, and direct composite manufacturing.

3.1.1 Stereolithography

3D Systems' line of stereolithography (SL) machines consists of the Viper si2, SLA 3500, SLA 5000, and SLA 7000. The machines, all of which use solid-state lasers to harden photopolymers, range in price from about $180,000 to $800,000.

The detail, accuracy, and surface finish of the 3D SL models have improved dramatically over the last several years. Most users of RP would agree that SL produces the best-looking RP models, from an aesthetic standpoint. Also, the physical properties of the photopolymers have improved significantly. Some of the most recent materials, from companies such as Vantico and DSM Somos, have been compared to popular thermoplastics such as polypropylene and acrylonatrile butadiene stryrine (ABS). Indeed, the materials have improved, yet one must keep in mind that an SL model's properties can change over time and this change can be accelerated by light, heat, moisture, and chemicals.

3.1.2 Selective Laser Sintering

In mid-2001, 3D Systems acquired DTM, the U.S. company that developed and commercialized Selective Laser Sintering (SLS). SLS can produce among the strongest and most useful models and prototype parts in the industry. Companies routinely produce SLS models for demanding fit and functional testing applications. The powder and CO_2 laser-based process uses materials such as polyamide (nylon), glass-filled polyamide, and polystyrene, so that laser sintered parts more naturally fit into the design, prototyping, and manufacturing process.

Currently, 3D Systems offers the Vanguard SLS system, which sells for about $320,000. The machine is capable of processing the materials named above, as well as an elastomer named Somos 201, foundry sands, and a stainless steel named LaserForm ST-100. The stainless steel is especially useful for producing steel parts and tooling components such as core and cavity inserts for plastic injection mold tooling. The sintering of the plastic binder coated steel powder produces porosity of about 40%, so the parts are infiltrated in an electric kiln-style oven with bronze to make them fully dense. Infiltrated parts perform similarly to P20 tool steel.

3.1.3 Multi-Jet Modeling

Multi-Jet Modeling (MJM) uses inkjet printing technology to deposit thin layers of material. The company's ThermoJet model produces wax parts with good up-facing surfaces. The down-facing surfaces are relatively rough due to the removal of the support structures. Companies have found ThermoJet models to be useful for design visualization and communication, as well as for investment casting patterns. The machine cost is about $50,000.

In mid-2002, 3D Systems announced the InVision si2 3D printer. It uses the same basic MJM jetting technology, but instead deposits and hardens acrylic photopolymer. The support material is a soluble material that washes away, similar to the supports from the *Objet Geometries* company. Although they do not offer the strength of some SL models, the models that have been shown to date are impressive.

3.1.4 Direct Composite Manufacturing

Direct Composite Manufacturing (DCM) is the name given to 3D Systems' OptoForm technology. OptoForm was a French company that 3D acquired in early 2001. Subsequently, 3D partnered with DSM Somos to form OptoForm LLC. Most of the company's resources are housed at 3D Systems' headquarters facility in Valencia, California.

The OptoForm technology is similar to stereolithography, except that it uses pastes instead of liquid photopolymers. This opens up a wide range of possibilities for composite, ceramic, and metal parts. The process is said to be fast and relatively accurate.

3.2 Cubic Technologies

Cubic Technologies, located in Carson, California, was formed in late 2000. However, its technical foundation is a process called Laminated Object Manufacturing (LOM) that was developed and commercialized by the former Helisys Company of Torrance California. Helisys patented LOM in 1988. Cubic Technologies is similar to Helisys in its products and services. The company is manufacturing and selling its 1015 Plus and 2030H systems for $69,500 and $179,500, respectively.

Laminated Object Manufacturing (LOM) is paper lamination technology. The technology is essential a fusion of cross-sectional cutouts. LOM was one of the first RP technologies to develop. Consequently, it was among the first to catch on. It enjoyed a relatively strong and growing customer base in the 1990s, but experienced difficulty in keeping pace with competitive developments and improvements. Consequently, sales began to flatten and then decline in the 2000 to 2001 time frame. Cubic is now trying to regain its position within the RP industry.

3.3 Optomec

Optomec has commercialized the Laser Engineered Net Shaping (LENS) technology that was originally developed at Sandia National Laboratories. The company's LENS 750 and LENS 850 machines (both $440,000 to $640,000) are capable of producing parts in stainless steel, H13 tool steel, titanium, tungsten, copper, aluminum, and superalloys, such as Inconel. The LENS machines produce near net shape parts by injecting metal powder into the path of a focused Nd:YAG laser. Although near net-shape, the surfaces of the resulting parts are very rough and require final machining.

The company sold an increasing number of systems from 1999 to 2000, but sold only one in 2001. Part of the reason may be that the company shifted much of its focus and resources to the development of Macroscopic Integrated Conformal Electronics (MICE), a $9 million program sponsored by DARPA. The objective of the work is to develop a direct-write, maskless process and associated deposition tool to permit the rapid manufacture of very compact and lightweight electronic systems.

3.4 The POM Group

The Precision Optical Manufacturing (POM) Group is a minority owned and operated business, founded in 1998 and operates its research facility in Auburn Hills, Michigan. The company is currently commercializing Direct Metal Deposition (DMD), a process similar to LENS. The University of Michigan conducted much of the work for development of this technology under a contract from the U.S. Department of Energy. The process uses a CO_2 laser and powder feed system to produce metal parts from thin layers. The parts are near net shape, so they also require finish machining.

The DMD technology is capable of processing nickel superalloys (such as Inconel and Hastalloys), cobalt superalloys, tungsten-based alloys, copper-based alloys, cermet alloys, tool steels, and other metals. The machine is also capable of producing functionally graded materials with automated dispensing control of up to four powdered metals.

The POM second-generation machine, the DMD 5000, is capable of producing parts as large as 1525 x 500 x 460 mm (60 x 20 x 18 inches). The machine uses a CNC motion system with a 4th axis spindle. In 2002, the company installed its smaller DMD 3000 at the University of Louisville for research and development purposes. The DMD machines are available for lease and sell for $750,000 to $1 million.

3.5 ProMetal

The ProMetal division of Extrude Hone Corporation has been developing MIT’s 3Dimensional Printing (3DP) process for metal part fabrication for many years. However, it wasn’t until the 2001 to 2002 time frame that development and commercialization activity came to life. Currently, several ProMetal initiatives are underway, including a $10.8 million Office of Naval Research project. Its purpose is to integrate ProMetal into the development and repair of weapon systems.

The process uses inkjet print heads to deposit a binder onto the surface of metal powder. Layer by layer, the machine builds metal parts in 316L or 420 stainless steel. A furnace cycle burns out the binder and brings the parts to full density using a bronze infiltrant. The final part consists of about 60% steel and 40% bronze.

Late in 2001, the company introduced its R4 and R10 machines for $275,000 and $650,000, respectively. The R4 offers print heads with 8, 16, or 32 jets, while the R10 offers 8, 32, and 96 jets. Unlike laser systems, the ProMetal R Series of machines offer the capability to generate multiple parts simultaneously and the interchangeable build chambers accommodate quick turnaround between jobs. In 2002, ProMetal introduced its R2 machine for an introductory price of $150,000. The company sold four of its systems in 2001, but expects significant sales of this system in the future.

3.6 Sanders Design International

In 2001, Sanders Design International (SDI) began to sell its Rapid ToolMaker (RTM) system commercially. Initially, the system was developed from Phase I and Phase II Small Business Innovation Research (SBIR) contracts with NASA's Marshall Space Flight Center. The goal of the work was to produce precision prototype patterns for aerospace tooling applications.

Similar to Solidscape's ModelMaker II and PatternMaster systems, the RTM system uses a print head to deposit a wax-like build material and a second head to deposit a soluble support material. The RTM machine offers two optional heads for bulk jetting, a method of filling interior areas that do not require high precision. The RTM system sells for approximately $120,000

3.7 Solidica

Solidica, Inc. was founded in 1999 and is located in Ann Arbor, Michigan. The company is currently developing and commercializing a patented process they call Ultrasonic Consolidation (UC), which is based on ultrasonic welding. The Ultrasonic Consolidation (UC) welds 25 mm (1 inch) wide aluminum alloy tape. The process removes unwanted material using CNC milling. One possible advantage to the system is producing deep grooves and other high aspect ratio features that would otherwise require Electrical Discharge Machining (EDM). Another possible benefit is the option of embedding small components and wires, such as optical fiber, in between the layers of tape. This has captured the attention of companies such as BAE Systems in the UK.

The company secured four beta test sites in 2001 for its machine, named Formation 2436. Solidica began production sales during the second half of 2002. Initially, the company is targeting the market for injection mold tooling. The machine is priced at $465,000.

3.8 Solidscape, Inc.

Solidscape Inc., formerly known as Sanders Prototype is located in Merrimack, New Hampshire and sells two types of ink-jet-based machines, the PatternMaster and ModelMaker. They have also introduced the T66 3D Modelling System. Most customers use Solidscape machines to produce relatively small, but precise, wax patterns for secondary processes, such as investment casting in the jewelry and medical industries.

One the most interesting applications of the technology are at a U.S. medical device company, Interpore Cross International. The company is operating 32 Solidscape machines, 24 hours per day, seven days per week, to produce wax patterns for titanium spinal implants.

The machines are capable of producing layers as thin as 0.0125 mm (0.0005 inch), resulting in a very good surface finish. However, the process is slow, and best suited to for making small parts and patterns. The ModelMaker II typically sells for approximately $67,000, while the PatternMaster sells for about $77,000.

3.9 Stratasys, Inc.

Stratasys is a publicly traded company under the stock symbol of NASDAQ: SSYS. They are located in Eden Prairie, Minnesota and annual sales are approximately $38 million. With its patented Fused Deposition Modeling process, Stratasys has carved out a niche with machines that produce strong parts for demanding fit and functional testing applications. All of its machines are capable of producing reasonably accurate parts in ABS plastic, a popular material for injection molded parts.

The company's current product line of machines includes the Dimension, Prodigy Plus, FDM 3000, FDM Titan, and the FDM Maxum. The machines range in price from $29,900 for the Dimension to $250,000 for the Maxum.

One of the company's newest machines, the FDM Titan, is capable of processing not only acylonatrile butadiene styrinbe (ABS), but also high temperature materials, including polycarbonate (PC) and polyphenylsulfone (PPSF). PC offers excellent impact strength, while PPSF resists chemical such as gasoline, methanol, antifreeze, and acids such a sulfuric acid. This opens up several rapid prototyping and testing opportunities that were before impossible. Many of the FDM machines offer a support system called WaterWorks. The WaterWorks system makes it possible to dissolve away the support structures using a warm water wash. WaterWorks also makes it possible to produce moving parts and complete mechanisms and assemblies, similar to what can be done with laser sintering and Objet's PolyJet technology.

In early 2002, Stratasys surprised the world of rapid prototyping when it introduced the Dimension product, making it the lowest priced RP machine available in the U.S. The company has been aggressively trying to position it in a different class, hoping to develop new markets.

3.10 Z Corporation

The Z Corporation has been successful in introducing relatively inexpensive 3D printing to companies worldwide and is known for commercializing MIT's 3DP technology for concept modeling and applications that do not require rigorous physical testing. Parts from the company's machines do not offer the best strength, accuracy, or surface finish, but the machines are very fast, perhaps the fastest on the market, and the materials are relatively inexpensive. Also, the machines print in full color, opening up a realm of new possibilities in 3D printing and rapid prototyping.

The Z Corporation Company's machines use either a food-grade starch powder or a plaster powder. Parts from the machine are relatively fragile without any secondary operations. One of many methods of improving strength is to infiltrate molten wax into the part. Another method is to infiltrate the part with cyanoacrylate, also known as super glue, resulting in a much stronger part. A third option is to use an infiltrant product named zi580 from Vantico. Users can apply it with a spray gun, a brush, or by dripping it onto parts.

The company offers the Z400, Z406, and Z810 machines, ranging in cost from $33,500 for the monochrome Z400 to $175,000 for the much larger Z810. The Z400 uses a single print head that houses 128 jets, while the Z810 uses six *HP* print heads, each housing 300 jets. The company's Z406 color machine, considered the company's flagship 3D printer, uses four heads with a total of 1,200 jets. This makes it possible to produce a part the size of a football in about two hours.

In 2002, Z Corporation introduced a method named ZCast. It is a process of printing molds used to produce metal castings. The process does not produce castings that are on par with high-end castings, but it is incredibly fast (one to two days) and the castings are acceptable for many prototyping applications.

4.0 Machines from Europe

Through most of the 1990s, few companies in Europe developed and sold RP machines. EOS was the exception. This is beginning to change with companies in Germany and Sweden entering the market. Leading European companies in the field of RP include two Swedish companies, Arcam and Speed Part; and four German companies Envision Technologies, EOS, F&S, and Generis.

4.1 Arcam AB

Arcam is a Swedish company, founded in 1997. Arcam has developed a free form fabrication (FFF) technique utilizing Electron Beam Melting (EBM) that they began to commercialize in 2001. The EBM process is similar to laser sintering of metal. The process fuses metal powders layer by layer to form strong metal parts. EBM parts are nearly 100% dense, but the surface of the parts is very rough and requires finish machining.

The Arcam EBM S12 model sells for $500,000 and is capable of processing two materials. One is H13 tool steel, while the other is a powder called Arcam Low Alloy Steel. The company's primary target market is production tooling.

4.2 Envision Technologies GMbH

Envision Technologies, also known as Envisiontec, is a start-up company based in Marl, Germany. The company has two major products. One is their 3D Bioplotter for the medical market. The other is a rapid prototyping system named Perfactory®. The system uses acrylate photopolymers and Digital Light Processing (DLP) technology from Texas Instruments. Visible light is projected from underneath through a glass plate onto the bottom side of a thin layer of photopolymer. The systems images and solidifies an entire layer at once, so it offers potential speed advantages over SL technology. The company began to sell beta systems in Europe in late 2001 and early 2002 and has priced the Perfactory system at about $44,000.

4.3 EOS

EOS GmbH of Germany offers a family of laser sintering (SL) machines that compete with 3D Systems' SLS machines. EOS's strategy has been to commercialize a specific machine for each class of material: one for plastics, one for metals, and one for foundry sands. The company has been in the business of manufacturing RP machines since 1990 when it began to produce SL systems. The company stopped SL machine production in 1997 and began to concentrate entirely on LS. It is the only European RP machine manufacturer with a significant installed base of customers.

The company sells machines named EOSINT P, EOSINT M, and EOSINT S that are priced from $300,000 to $850,000. (The P, M, and S designate whether the machine is dedicated to plastic, metal, or sand.) The company's EOSINT P 380 and EOSINT P 700 process polystyrene, polyamide, and glass-filled polyamide powders. The EOSINT P 700 is a large machine that uses dual lasers to speed the sintering process.

Customers of the company's EOSINT M 250 machine can choose from either a proprietary bronze-based metal or a steel-based powder. The machine sinters both powders directly, rather than sintering binder-coated powder—the method used with SLS from 3D Systems. The binder approach sinters more quickly, but it requires an oven cycle that takes time and costs money. EOS's metal powders, DirectMetal 20 (bronze-based) and DirectSteel 20 (steel-based) permits users to produce layers as thin as 20 microns (0.0008 inch). This results in impressive surfaces and feature detail and minimizes finish machining and handwork. EOS also refers to its metal sintering as Direct Metal Laser Sintering (DMLS).

The EOSINT S 750 foundry sand machine is used to produce molds and cores for sand castings and uses dual lasers to speed the sintering process. EOS has named the process DirectCast. In 2002, EOS began to market its materials and machines in the U.S.

4.4 F&S

Fockele and Schawarze GbR was founded in 1990 in Germany and the F&S Stereolithigraphiietechnik GmbH was established in 1992. F&S GmbH has commercialized a process called Selective Laser Melting (SLM) that is similar to laser sintering. The company has worked for years with the Fraunhofer Institute for Laser Technology in Aachen, Germany to develop SLM. The product, named FS-Realizer SLM, produces fully dense steel parts using powder particles 20 microns (0.0008 inch) in size, according to F&S. The company is positioning the SLM machine for the manufacture of steel molds. The machine sells for about $280,000.

4.5 Generis GmbH

Generis GmbH of Germany was founded in May 1999 and is commercializing their GS 1500 system. The machine uses wide area inkjet printing to bond layers of sand into large sand molds and sand cores for cast metal. A primary advantage of this technology over the traditional process is the elimination of the tool making step. The company has successfully printed molds for turbine blades, as well as a difficult water core jacket for cylinder heads. A build chamber full of sand weighs several tons. In November 2000, Generis formed a strategic relationship with Soligen to develop and market the system in the U.S.

4.6 Speed Part AB

Speed Part AB is a Swedish company that has developed and patented a new RP technology. The process uses heat from infrared lamps to sinter layers of plastic powder through a mask printed on a glass plate. The first machines have an A4-sized build envelope. While the fusing process for each layer takes about one second, the entire cycle time for a layer is estimated at about 10 seconds.

5.0 Machines from Japan

Several companies in Japan have commercialized machines for rapid prototyping. These include: Autostrade, CMET, Denken Engineering, Kira, Meiko, Sony/C-Mec, Toyoda Machine Works, and Unirapid. Six of the eight machine manufacturers in Japan currently sell systems based on some form of stereolithography. Over the past decade, annual sales Japanese producers have been limited to 10 to 30 units per company.

5.1 Autostrade Co., LTD.

Autostrade manufactures the E-Darts solid printer. The RP machine is about the size of a microwave oven. Similar to the Perfactory machine from Envision Technologies, the E-

Darts machine produces photopolymer parts with the build platform above the part instead of below it. The machine uses a laser, however, as the light source. The machine sells for about $25,000 in Japan and, in late 2001, they began test marketing the product in Europe.

5.2 CMET Inc.

In 2001, Teijin Seiki announced that it had completed the acquisition of NTT Data CMET. Teijin Seiki's Soliform business (based on the Somos machine technology it licensed from DuPont in 1991) merged with NTT Data CMET to form a new company named CMET Inc. CMET, which stands for Computer Modeling and Engineering Technology, operates as a business unit of the Teijin Seiki Group. **B**ased on unit sales and estimated revenue volume, CMET is the leading RP machine manufacturer in Japan and was the first to offer RP systems in Japan.

CMET offers several stereolithography machines including the Soliform-250B, Soliform-500C, SOUP II 600GS, Soliform Multi 600, and the Soliform Multi 1000. (The Soliform name came from DuPont, while the SOUP name came from NTT Data CMET and stands for Solid Object Ultraviolet Laser Plotter.) These products range in price from about $250,000 for the Soliform-250B to $1.25 million for the Soliform Multi 1000. The machines in the company's "Multi" series offer either dual or quad lasers. Running multiple lasers enhances build speed.

In 2002, the company announced the Rapid Meister series of stereolithography machines, including the Rapid Meister 2500F, the Rapid Meister 6000, and the Rapid Meister Multi. The main differences between the three are size, resolution, build speed, and price. Simultaneously, CMET announced that it would introduce a new photopolymer from Asahi Denka that would offer physical properties similar to ABS plastic. Parts from the CMET machines are impressive and are on par with those created with stereolithography machines from 3D Systems.

5.3 Denken Engineering

For nearly a decade, Denken has offered small and relatively inexpensive stereolithography machines. The Denken system uses a technology developed by the University of Tokyo Design Engineering Laboratory that solidifies each layer of photopolymer by freezing. The company's products are the SLP-4000R and SLP-6000 and sell for about $24,000 and $121,000, respectively. SLP stands for Sold Laser Diode Plotter. The machines are relatively slow and parts are small, so, to date, the products have been targeted mainly at university and research institutions as opposed to industrial users.

5.4 Kira

Kira's Solid Center machines use adhesive and an *x-y* plotter system and blade to laminate and cut sheets of paper. The finished parts resemble wood. The company's PLT-A4 system ($55,000) uses standard A4 size sheets. Consequently, Kira says that it has commercialized the world's first plain paper 3D printer. The PLT-A3 ($73,000) uses paper from a spool.

In the 1990s, interest in paper lamination systems for rapid prototyping was nearly as strong as for SL, FDM, and other systems. The speed, accuracy, and material properties from competitive processes have improved dramatically, so it has been difficult for paper lamination systems to keep pace. Consequently, interest in paper lamination has declined, particularly in the U.S.

5.5 Meiko

Meiko manufactures a small stereolithography machine that offers good detail and surface finish. The company has targeted designers and manufacturers of jewelry and has experienced some success in that market. The company offers the LC-315, LC-510, and LC-610 models that range in price from about $63,000 to $115,000.

5.6 Sony/D-MEC (Design Model Engineering Center)

Sony/D-MEC was the second Japanese company to manufacture and sell RP systems. The company is comprised of a partnership between Japan Synthetic Rubber (JSR) for materials development and company management, and Sony for the manufacture of the SL equipment. The company currently offers the Solid Creation System (SCS) family of SL systems. The machines range in price from about $212,000 to $1 million. Models and prototype parts from the machines are impressive. Users would agree that they offer quality that is similar to those created with stereolithography machines from 3D Systems.

In May 2003, Sony Precision Technology America, Inc. of Lake Forest, California introduced the D-MEC machines to the U.S. market. Introducing machines into the U.S. was made possible through a licensing agreement with 3D Systems. Such an agreement is a requirement of the U.S. Department of Justice Antitrust Division.

5.7 Toyoda Machine Works

In 2000, Helisys (a company that "transformed" into Cubic Technologies) announced a technology licensing agreement with Toyoda Machine Works of Japan. The agreement permits Toyoda to manufacture and sell LOM machines in Japan. In Spring Q2 2000, Toyoda showed its LOM SC400 ($73,000) at an exhibition in Tokyo. The company has since begun to offer the LOM-2030H—a product that is similar to Cubic Technologies' 2030H.

5.8 Unirapid

Unirapid (formerly Ushio) offers a stereolithography machine that uses a lamp and fiber optics to deliver the ultraviolet (UV) light. The machine, named the URII-SP1502, sells for about $64,000. The machine offers a small work volume, although parts from it offer impressive detail and surface finish.

6.0 Machines From Other Parts of the World

In addition to the United States, Europe, and Japan, RP manufacturing is developing in China, Singapore, and Israel.

6.1 China

The market for RP in Mainland China has grown over recent years. Several American companies, including 3D Systems and Stratasys, sell their RP products in China. Organizations in China are also developing and commercializing RP machines of there own. Most of the R&D work occurs in universities. The institutions enjoy large numbers of graduate students that are willing to do in-depth research in this area. One institution has 30 graduate students; another reportedly has 130 students focused on RP. The universities form companies that offer rapid prototyping services and sell RP machines. It’s unclear whether the sales force are from within the university and whether the transactions occur on campus. It is clear, however, that the university unit responsible for the RP technology influences the company to a great extent.

Most of the machines developed to date are based on western technology. The Chinese companies have introduced SL, SLS, LOM, FDM, and forms of 3D printing using inkjet technology. The technology is progressing in China and, in fact, some of the FDM parts are as impressive as those from Stratasys.

6.1.1 Beijing Yinhua Laser Rapid Prototypes Making and Mould Technology Company Ltd.

Beijing Yinhua is an effort launched from Tsinghua University, a Beijing institution that is viewed in China similar to how MIT is viewed in the U.S. The work in Rapid Prototyping is led by Professor Yongnian Yan, Director of the Center for Laser Rapid Forming at the university.

Professor Yan leads one the largest RP research groups in the world, including six professors and 25 PhD students — all working together to advance the technology and its application in China.

The university has developed and commercialized FDM technology that it calls Slicing Solid Manufacturing (SSM) and a LOM approach called Melted Extrusion Manufacturing (MEM). The organization is also selling a “multifunctional” system that combines SSM and MEM in a single machine. The machines range in price from about $40,000 to $120,000. The first RP machines from Tsinghua were sold in 1996. Beijing Yinhua also operates a service bureau on campus in one Yan's labs.

Professor Yan and his team are also dedicating major resources on the development of machines for medical applications. One machine builds porous scaffold structures for tissue engineering and cell generation. Two years of testing on 105 rabbits and 42 dogs has shown compelling results. The team is also developing a process and stereolithography system for the creation of clear plastic aligners to straighten human teeth. The process is nearly identical to the Invisalign process from Align Technology in the U.S.

Tsinghua University, with Yan's leadership, hosted the second International Conference on Rapid Prototyping and Manufacturing (ICRPM 2002 Beijing) in August 2002. The event, which included a small exhibition, attracted more than 100 attendees from 16 countries. The event was sponsored and supported by the National Natural Science Foundation of China and the Chinese Mechanical Engineering Society. The Global Alliance of Rapid Prototyping Associations (GARPA) held its Global Summit 2002 meeting at the conference. The first Chinese conference was held in 1998 and the third conference is scheduled for 2006.

6.1.2 Wuhan Binhu Mechanical & Electrical Co.

This company was launched at Huazhong University of Science & Technology in Whuhn, Hubei, China. The organization is developing and selling machines that are very similar to SLS and LOM. The SLS machine sells for about $120,500, while the two LOM machines sell for about $30,000 and $72,000. A third and larger LOM machine is in R&D.

Research in RP began at the university in 1991 and has since received endorsements from the Department of Science & Technology, the Department of Education, and other Chinese agencies. The introduction of the first commercial system was in 1997.

6.1.3 Shanghai Union Technology

This company is developing and selling a family of SL systems consisting of three machines. The machines differ in laser power and build volume. All three use the Magics RP software from Materialise of Belgium for STL file preparation.

Another class of machine from the company is a concept modeler that uses a 100-watt short arc mercury lamp as its light source and resin produced in-house. Its build volume is 300 x 300 x 200 mm (12 x 12 x 8 inches) and is priced at $25,000.

The company offers rapid prototyping and rapid tooling services and expects to introduce an entirely new type of RP machine in the foreseeable future. As its name implies, Shanghai Union Technology (also known as UnionTech) is based in Shanghai. It employs 40 people.

6.2 Singapore - Kinergy

One company in Singapore, Kinergy, has been developing and distributing RP systems since 1995. Kinergy offers systems based on paper lamination and Fused Deposition Modeling (FDM) technology. The machines resemble the LOM technology from Cubic Technologies and FDM from Stratasys. A third machine offers both paper lamination and FDM-type capabilities. Kinergy's primary market is China, where Kinergy has a branch office and a service center. However, systems have also been installed in Taiwan, Indonesia, Germany, and Japan.

6.3 Israel

Israel has a long history of contributing to the RP industry. There are currently two producers of RP technology, Objet and SDolidimension. A third company, Cubital, shut down its operation in 2001. Cubital was among the first to commercialize an RP system and shipped machines to more than 20 countries including the U.S.

6.3.1 Objet

Objet has developed new-generation RP technology, named PolyJet, based on inkjet printing technology. The PolyJet technology was first introduced in early 2000, but the production version of the system did not begin to ship until the second half of 2001. The machine uses 1,536 jets to deposit two proprietary photopolymers. One photopolymer is the build material, while the other is a water-soluble support material. The print head assembly contains UV lamps that supply the light needed to solidify the resin. The machine produces layers that are 20 microns (0.0008 inch) thick, so the surfaces of the parts are very good and require little or no hand finishing, depending upon how they are going to be used.

Objet had developed its own proprietary acrylate photopolymers. The materials are suitable for many form and fit applications, but they are not strong enough for rigorous functional testing. If the company expects to expand the range of applications for its PolyJet technology, it will need to improve its materials or consider a partnership with a material supplier.

Objet's first machine, named Quadra, sells for $69,000 in the U.S. The second machine, named QuadraTempo, is about 20-25% faster and sells for $79,000. After Objet introduced these systems, 3D Systems countered with its InVision si2 3D printer, a product that operates similarly.

6.3.2 Solidimension

Israeli-based Solidimension is developing a machine that laminates thin layers of plastic to form parts. The small desktop machine uses a knife mounted to an *x-y* plotter mechanism to cut sequential layers from a roll of plastic material, and bonds them together with a solvent. The manufacturer expects to offer PVC, ABS, and polycarbonate. The layer thickness can range from 0.05 to 0.2 mm (0.002 to 0.008 inch). The company has been developing the machine since January 2000 and expects to sell the machine for less than $30,000.

7.0 Other Developments

Since stereolithography was introduced commercially in 1987, there has been tremendous growth and development of rapid prototyping technology. Today, there are 26 manufacturers of rapid prototyping machines and more than 40 service providers. The technology is also advancing to encompass rapid tooling, of which there are over 20 techniques presently being developed. The following describes just a few of the more prominent developments.

7.1 AeroMet

AeroMet, a subsidiary of MTS Systems Corp., has developed a process it calls Laser Additive Manufacturing (LAM). The company uses powder titanium and a CO_2 laser to form near shape parts layer-by-layer. The powder fuses together at the point where the laser contacts the target substrate. The fully dense “preform” is then heat-treated and finish machined. The build volume is 3 x 3 x 1.2 m (10 x 10 x 4 feet).

While similarities between LAM and other methods exist, the application and target market are different. The company is focusing almost exclusively on the production of large titanium parts for the aerospace industry. Boeing, Lockheed Martin, and Northrop Grumman confirm that LAM components exceed the requirements for static strength and fatigue for the replacement of conventionally manufactured parts.

7.2 CAM-LEM

CAM-LEM, Inc. is commercializing a lamination process that builds ceramic and metal parts. (CAM-LEM stands for Computer-Aided Manufacturing of Laminated Engineering Materials.) The process is similar to LOM technology. Much of the development work was completed at Case Western Reserve University.

The CAM-LEM process can produce layers of varying thickness. After fabrication, the parts are processed in an oven to remove the binder and support material. The oven sinters the material to 99% density, although parts can shrink 16% during the process.

CAM-LEM has been working as a service provider rather than selling systems. It offers a suite of technologies that allow complex ceramic and metal parts to be made more economically. Ceramic parts produced conventionally are very simple because of processing limitations. In contrast, CAM-LEM's technologies permit more complex shapes.

7.3 MEMGen

MEMGen launched its operation in early 2002 to commercialize technology developed at the University of Southern California. The Electrochemical Fabrication (EFAB) process is based on electroplating techniques and is a batch part fabrication method suitable for producing devices from the micron scale to the mesoscale of a few millimeters.

The first available build material is nickel, but any material that can be plated is a future possibility, including most metals. Company officials say they're working on material systems that may result in parts made from insulators. Parts can have hundreds of layers that are patterned through masks. These masks are generated directly from STL files, so any application that uses CAD is a candidate to use the process.

7.4 Mesoscale Integrated Conformal Electronics (MICE)

The DARPA Mesoscale Integrated Conformal Electronics (MICE) program is investigating a number of direct-fabrication methods aimed at simplifying processing and providing greater flexibility than is possible using existing technologies. Mesoscale electronics occupy a middle ground between integrated circuits and surface-mount components, and have important applications in military, communications, and medical areas.

Optomec is developing a MICE process called Maskless Mesoscale Material Deposition (M^3D). It has some similarities to the company's LENS work, but a laser is not used for bonding. Powder or paste materials in a carrier gas stream are made to stick without damage to a low-temperature substrate. Passive devices such as resistors, capacitors, inductors, and conductive traces can be formed. The process has also been used experimentally to fabricate fuel cells and batteries.

7.5 MicroTEC

MicroTEC of Germany, founded in 1996, offers miniature manufacturing services based on photopolymers. Two basic but related processes are offered under the RMPD (Rapid Micro Product Development) trade name. The first method splits the exposing laser into a number of individual parallel beams, which are moved in a vectorial fashion over the surface of the photopolymer to harden multiple parts at one time. This process is analogous to stereolithography and can produce virtually any shape.

The second method uses an expanded light beam and masks to expose multiple part cross sections over the entire surface of the photopolymer at one time. This method is faster for shapes that have simple cross sections or ones that don't vary much over their length.

In both cases, the emphasis is on the batch production of many parts at one time. The company says that it is possible to fabricate as many as 150,000 parts per hour on a single machine using the mask technique.

7.6 Specific Surface

This company holds the 3DP license from MIT for the manufacture of filters for a wide range of applications. Specific Surface uses machines purchased from Soligen for the production of the filters. Specific Surface's process, called CeraPrint, allows precise control of pore size and placement, creating filters with large and complex internal surface areas. This approach eliminates the need to cement or weld separate parts together for large filters, saving time and money.

7.7 SRI International

For several years, SRI International has been developing a process that it calls Direct Photo Shaping. It is mechanically similar to stereolithography, but uses a deformable mirror device (DMD) instead of a laser to expose an entire layer at one time. The DMD is a semiconductor device that has thousands of tiny, controllable mirrors that are switched on or off to reflect light in a 2D image onto the surface of photopolymer.

SRI has produced experimental systems that can fabricate 200 layers per hour, in layer areas of 150 x 150 mm (6 x 6 inches). These systems are capable of building layers as thin as 12.5 microns (0.0005 inch)

7.8 Therics

Therics uses a 3DP license from MIT to manufacture medical products ranging from time-release medications to resorbable scaffolding, and implants for cartilage, tendon, and bone substitutes. The Food and Drug Administration (FDA) has validated its process, although the products themselves are still under development.

8.0 Defense Opportunities

With the end of the cold war, our defense policy shifted from modernization through replacement to one of weapon system sustainment. Many weapon systems are more than 25 years old with options being considered to extend the life of several systems to over 50 years. While the basic mission of many of these systems has not changed from their original operational capability requirements, and many of the subsystems have undergone upgrades, the ravage of time and exposure to the elements requires occasional replacement or repair of structural parts. As this occurs, vendors may no longer exist, processes used are obsolete, metal alloys originally specified may not be available, tooling has been destroyed, inventories have long been depleted, if they existed at all, and the original Technical Data Packages exist only in paper form, if at all.

When an item is out-of-stock, the supply chain is slow to respond, easily taking up to 14 months to deliver with less than 25 percent of that time allocated to true manufacturing. While hard-to-find and out-of-stock parts make up less than 1 percent of the overall demand, they are often the pacing item for repairs. Suppliers frequently require minimum orders that far exceed the cost of small lot buys. Once manufactured, approximately 30 percent of the parts used are stored locally with many others available within 48 hours using systems that are often vulnerable.

Parts obsolescence not only occurs for weapons systems, but in many cases the infrastructure used to maintain or manufacture weapon systems is similarly dated and equally difficult to maintain in their own right. For example, the cranes in a Navy Shipyard are often foreign supplied and can be 50-60 years old.

One of the most pressing problems the DOD maintenance community continues to face is the ability to affordably produce or repair short runs of parts in a timely manner which exhibit conventionally manufactured material properties. Once this is achieved, parts obsolescence no longer exists, inventories, and the cost associated with them, can be substantially reduced, complex maintenance legacy systems can be dismantled, and deployed forces can be more easily supported.

Maintenance of aging weapon systems, the manufacture of functional first articles, and the manufacture of complex parts having unique features are clearly the greatest long term opportunity for the application of rapid prototyping technology. However, opportunities exist in the near term for application to nonstructural components, tooling, and engineering models using readily available technologies.

While progress in the direct manufacturing or repair of metal parts continues to be made as a result of ongoing investment by a number of Federal agencies, the high initial cost and risk associated with their use continues to limit their deployment and diffusion within DOD and their major weapon system contractors.

8.1 Depot Level Maintenance and Repair

Depot level maintenance entails the major repair, overhaul, or complete rebuilding of weapon systems, end items, parts, assemblies, and subassemblies; manufacture of parts; technical assistance; and testing. The bulk of the workload at DoD Depots is associated with ships and aircraft and to a lesser degree, missiles, combat vehicles, and other ground equipment systems. Overall, DOD spends about $13 billion annually for depot-level maintenance and repair work.

Material is a major factor in the use and application of RP technology at U.S. Military Depots and Arsenals. The materials used at the Depots vary broadly. Superalloys and titanium alloys are widely used in aircraft applications. Cu-Ni alloys and Monel are widely used in ship-based applications with titanium widely used in submarines and newly commissioned ships. Titanium is widely used in air weapon systems whereas molybdenum is widely used in underwater weapon systems. Aluminum and steel alloys are widely used throughout DOD. Metal matrix composites and ceramics have limited use today but their use is expected to increase over the next decade. Superalloys are primarily used in the hot section of gas turbine engines. Metal parts are generally machined from billets or cast. A very small, but growing, percentage is derived from powdered metals. HIP metal parts are generally limited to castings or high value added parts. A large number of parts (over 80% at a shipyard) fit within a 12 x 12 x 12 inches fabrication envelope.

Early rapid prototyping applications have focused on installation at Depot Level Maintenance and Repair Facilities where in-service engineering support, test, development and manufacturing functions are collocated and space, power, and environmental requirements can be easily accommodated. This approach encourages not only use in fielded systems but early integration into emerging systems in addition to providing access to more knowledgeable operators and accelerated approval of departures from approved materials and processes.

Currently, military depots and arsenals are using a broad range of conventional rapid prototyping technologies to aid in parts replacement and redesign. Capabilities and experience are generally shared through user networks. Newer technologies, with direct manufacturing capability, are just starting to appear in the depots with application to repair or replacement of less critical parts, such as brackets, electrical connectors, and fittings. More critical parts fabrication and repair remains in the R&D stage and includes gas turbine blades and vanes, valves, fasteners, and guidance housings. These technologies are expected to transition over the next several years. While technologies developed for large casting equivalents such as that available from AeroMet, will likely remain at central suppliers, smaller versions could be placed in depots and arsenals.

8.2 Field Level Maintenance and Repair

Field-level maintenance and repair comprises shop-type work as well as on-equipment maintenance activities. Intermediate or shop type work includes limited repair of commodity-oriented assemblies and end items; job shop, bay, and production line operations for special requirements; and manufacture of repair parts, assemblies, and components. DOD is estimated to spend about $25 billion annually for field-level maintenance and repair work.

To better understand the environment for field level repairs, a destroyer class ship has a small machine shop that includes a metal saw, lathe, drill, grinder, and welder. The total space occupied is approximately 20 feet x 20 feet x 6 feet high. Access is limited due to the narrow passages. A small storage area, approximately 10 feet x 4 feet deep x 6 feet high, is available for metal stock. Very few parts are stored onboard the ship with parts made or repaired including shafts, valves and fasteners. Metals used are primarily brass, Monel, and Cu-Ni alloys. Technical Data Packages are not available and parts are generally reverse engineered by dimensional inspection. Power on the ship is 440 VAC, 3 phase. Motion while at sea can become quite severe but is generally low. More demanding repairs are performed at forward area deployed depots or repair ships which are fully equipped and can perform high tolerance machining.

Field-level maintenance and repair using rapid prototyping technology has been limited by the harsh environment and lack of suitable portable systems. To begin to develop an understanding of how to overcome these challenges, the U.S. Army Tank-automotive and Armament Command National Automotive Center, has recently developed a test bed for field level maintenance that includes the necessary communication and manufacturing technologies located in a portable trailer. The Mobile Parts Hospital (MPH) capability includes satellite communication for part data transfer, hardware and software for part reverse engineering, direct metal deposition for rapid near net shape part fabrication and a compact multi-task machining center for final finish work on the near net shape parts.

The logistics footprint of the material deposition module once expanded for use is 20 feet x 24 feet, which is easily transported by air or could be installed on a suitable ship. The goal of the program is to compliment the existing supply systems and to provide a qualified part onsite.

8.3 Multi-functional and Smart Materials

While direct manufacturing of a single material into a functional part is an immediate goal for DOD, improvements in performance and capability can be achieved through architecturally controlled structures or integration of sensors, electronics or other functionality as the part is fabricated. Examples include the demonstration of porous metals for application to lightweight armor by Advanced Ceramics Research and graded metals for wear resistant surfaces by POM Company. In fabricating porous metal foams, metallic powder/polymer blends were extruded and patterned to form directional microstructures which when heated to remove the binder and sinter the metal powder, formed a continuous network of porosity. Graded structures were produced by controlling the powder deposition, powder composition, and laser heating process conditions resulting in a ductile steel core and a hard diboride surface.

8.4 Barriers to the Introduction of RP for Application to Functional Parts

Rapid prototyping technology, for the evaluation of fit and form, is now widely accepted by DOD and its suppliers as witnessed by the large number of equipment installations and model purchases from service bureaus. RP systems are generally limited to the first tier suppliers due to their high cost but incremental reductions in cost over time are resulting in further diffusion of the technology down to second and third tier suppliers. Application of RP technology to access fit and form has seen few barriers while application to functional parts continues to meet resistance due to a lack of technology maturity, the high cost of part qualification, and limitations on part size and composition. This resistance has been met with the application of RP to both critical and non-critical parts. Acceptance of repair and refurbishment of surfaces using RP has met with less resistance because the load bearing structure is not effected by the repair and the cost of qualification is frequently far less.

Methods available to introduce new materials and processes in DOD include qualification, first article testing, and waivers. Qualification programs are used to reduce the time, cost, and risk associated with the introduction of new products, materials and/or processes and to separate evaluation and testing from any specific acquisition or procurement. First article testing has been used for applications where a part of a particular material is produced infrequently and the cost of a qualification program cannot be justified.

Waivers

The requirement for part qualification can also be waived by the qualifying activity when supply of the part is deemed life or mission threatening and the part is considered suitable for use. Common guidelines for the waiver process have not been well established except for waiver approval made directly to the qualifying activity. An example of a frequent problem requiring a waiver is difficulty in getting a part made of the same metal alloy. A waiver to change the alloy is generally requested. Class I parts are more difficult to get waivers for, require first article destructive testing, and require material feedstock traceability. Once in the field, a waiver decision is made locally based on the nature of an impending operation and time to receive a qualified part. Waivers are rarely if ever provided for Class I parts when supported in the field. A champion for a new technology is beneficial to the waiver approval process. Once a waiver is allowed for one application it will only benefit other applications if the requirements are identical. Ultimately, as experience is gained by the ESA with a new material or manufacturing process the waiver process becomes easier.

Qualification

Two types of qualification programs exist, product qualification (QPL) and process/material qualification (QML). A QPL is used when the design and manufacturing process are mature and stable and will be used for an extended period of time with medium to high volume production runs. A QML focuses on qualifying an envelope of materials and processes rather than individual products. Under a QML, the manufacturing facilities, processes and materials, and other characteristics are qualified. Once qualified, they can be used to manufacture any part where the original capability has been exceeded without further qualification. A QML is more appropriate to complex parts where the cost of qualification would be excessive or create significant delays. A QML appears best suited to rapid prototyping technology applied to manufacture of functional parts.

Cost of Qualification

During qualification, both the manufacturer and DOD share in the cost. Exceptions are sometimes in the case of a small business without the resources, where limited suppliers exist, or where a limited number of parts are to be purchased, in which case, DOD pays for qualification. The cost is directly related to the qualification program requirements. For Class I parts in which the performance, quality, and reliability of the item are critical and the consequences of failure may be catastrophic to a mission, equipment safety and/or life, the requirements can be extensive and expensive. For Class IV parts in which the need for assurance of product performance, quality, and reliability is low to moderate, the cost of qualification is inherently low.

Noncritical parts are preferred candidates for use with rapid prototyping. A waiver is more likely to be granted in a timely manner at lower cost when the part is noncritical to system operation. Critical parts, such as Class I, require detailed analysis and re-qualification in a manner similar to that originally used. Critical part replacement could easily take up to 12 months and cost $100,000’s for first article testing. Critical parts are less frequently out-of-stock and therefore the least likely to benefit from RP technology.

The qualification program responsibility resides with the designated qualifying activity, which in most cases is the respective DOD Engineering Support Activity. The qualifying activity is responsible for reviewing design data, manufacturing processes and changes, qualification test data, on-going conformance testing, and qualification retention data. In the past, qualification requirements were specified in the applicable federal or defense specifications. Non-Government Standards are now commonly accepted.

A qualification program based on the materials and processes requires that critical steps in the manufacturing process be identified, monitored, tested, and controlled to assure continuous product performance, quality, and reliability. A baseline of the manufacturing process is established and approved with any changes potentially requiring re-qualification. This becomes especially critical for mobile manufacturing capability and has been the focus of the U.S. Army Mobile Parts Hospital technology development program. Once qualified, the level of surveillance to assure continued compliance is based on product life cycle, complexity, and criticality.

The Engineering Support Activity will generally determine the extent of testing for requalification based on what was performed on parts manufactured using the original material and process. Experience and comfort level with the material and process are also a determining factor. A detailed database is not required for a new material or manufacturing process because most applications have unique performance requirements.

For those applications where a technical data package does not exist or is not readily available, reverse engineering is performed through dimensional inspection and metal analysis. The original parts configuration is first captured in digital form through computerized dimensional inspection. Using these digital data, a wire frame is created, surfaced, and an IGES 3D model are developed. Rapid prototyping is used to verify dimensional accuracy of the digital data. If metal alloys identified from the analysis are not readily available, alternate alloys are selected which exhibit critical properties equal to or better than the original. The digital data and materials specification in combination with production and product assurance inputs form a complete Technical Data Package (TDP). Use of this TDP in the field is expected to require a waiver prior to acceptance by the qualifying activity.

As an example of the introduction of new materials and processes, DLA recently demonstrated the replacement of a welded mortar plate made up of a number of pieces with a lower cost casting. Both the material and process used to produce the part were changed. Even though a large Science & Technology database existed for the material and casting process, detailed engineering analysis of the part was required at a cost of approximately $15,000. Due to the critical nature of the part, requalification was also required at a cost of $250,000.

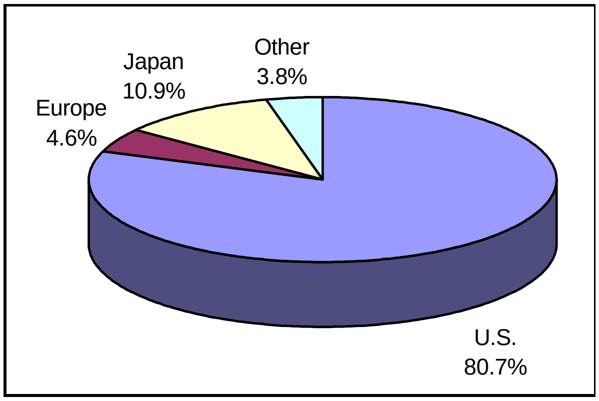
An example of the introduction of RP technology is the process underway for the qualification of laser net shaping technology provided by AeroMet. The AeroMet Company has been working with Boeing, Northrop Grumman, and the U.S. Navy in developing the necessary building blocks for process and product acceptance. Following the development of an industry lead specification, a proposal that includes product and process qualification was prepared for review by the Navy Engineering Support Activity. Their success is viewed to be based on a combination of a maturing technology having reported cost savings, champions within DOD and the user community, and knowledge of the qualification process.

The U.S. Army Mobile Parts Hospital (MPH) program is also addressing the issue of part/process qualification. This is particularly an issue when materials or prints are not readily available, especially if manufacturing parts in the field. One objective of the Mobile Parts Hospital program is to minimize material inventory and reduce the logistics “footprint”. Also, if blueprints and drawings are no longer available, spare parts must often be reverse engineered. Therefore, the tenet upon which the MPH is based is that parts made must be as least as good and, in most cases, with better properties than the component being replaced. Hence, MPH frequently makes a part from material with better properties than the material originally used, but at an overall lower cost when factoring the logistics issue and high level of confidence in the overall quality and potential performance of the component.

A property database for materials of interest is to be established and serve as a catalogue for in-service material selection and overall advancement of the utility of rapid prototyping.

9.0 Summary and Conclusions

The RP industry continues to expand. In 2001, more systems were installed, more material was consumed, and more applications for the technology were uncovered. The U.S. continues to dominate the production and sales of RP systems, as shown in the following chart. Nearly 81% of the systems sold in 2001 came from U.S. machine manufacturers, essentially unchanged from the three prior years. Japan’s segment declined for the second consecutive year, dropping by two full percentage points.



Source: Wohlers Report 2002

Figure 10. Global Source of RP Equipment Based on Sales

There are currently 33 different manufacturers of RP equipment globally that fall within five different categories of commercially available technologies. Each of these manufacturers can provide equipment to DOD and their suppliers today that satisfies the requirements of fit and form with some level of functionality using a range of materials. Further improvements in functionality is an area of increasing R&D focus which has attracted additional Federal investment and resulted in several equipment suppliers being close to providing commercial units. These commercial units are expected to provide near net shape fit, form, and function of commercially viable material compositions. While some post processing is required to achieve final tolerances, cost and schedule savings have been demonstrated.

Advances in RP technology over the next decade are expected to include a broader range of functional compositions, great proximity to net shape fabrication, system innovation to reduce cost, and heterogeneous devices containing added functionality. Due to the high risk nature of these innovations, continued federal investment will be required. Of high importance to DOD is the ability to successfully transition RP technology that can produce functional parts to the maintenance depots, field repair centers, and as close to the battlefield as Concept of Operations (CONOPS) requires. AeroMet and the U.S. Army Mobil Parts Hospital are providing the foundation for successful deployment of the technology as it continues to emerge. Critical to meeting this goal will be continued DOD investment and the development of guidelines for waivers and qualification programs which address the unique capability provided by rapid prototyping technology.

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