Japanese and World Technology Evaluation Centers

JTEC WTEC

JTEC/WTEC Panel Report on

Rapid Prototyping in Europe and Japan

VOLUME I. ANALYTICAL CHAPTERS

Friedrich B. Prinz (Panel Chair)
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JTEC/WTEC PANEL ON RAPID PROTOTYPING IN EUROPE AND JAPAN

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INTERNATIONAL TECHNOLOGY RESEARCH INSTITUTE WTEC PROGRAM

The World Technology Evaluation Center (WTEC) at Loyola College (previously known as the Japanese Technology Evaluation Center, JTEC) provides assessments of foreign research and development in selected technologies under a cooperative agreement with the National Science Foundation (NSF). Loyola's International Technology Research Institute (ITRI), R.D. Shelton, Director, is the umbrella organization for WTEC. Paul Herer, Senior Advisor for Planning and Technology Evaluation at NSF's Engineering Directorate, is NSF Program Director for WTEC. Other U.S. government agencies that provide support for the program include the National Aeronautics and Space Administration, the Department of Energy, the Department of Commerce, and the Department of Defense.

WTEC's mission is to inform U.S. policy makers, strategic planners, and managers of the state of selected technologies in foreign countries in comparison to the United States. WTEC assessments cover basic research, advanced development, and applications/commercialization. Small panels of about six technical experts conduct WTEC assessments. Panelists are leading authorities in their field, technically active, and knowledgeable about U.S. and foreign research programs. As part of the assessment process, panels visit and carry out extensive discussions with foreign scientists and engineers in universities and in industry/government labs.

The ITRI staff at Loyola College help select topics, recruit expert panelists, arrange study visits to foreign laboratories, organize workshop presentations, and finally, edit and disseminate the final reports.

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JTEC/WTEC Panel on

RAPID PROTOTYPING IN EUROPE AND JAPAN

FINAL REPORT

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In Memory of Richard S. Aubin
1948 - 1997

It was with great sadness that members of the JTEC/WTEC rapid prototyping panel learned of the death of fellow panelist Dick Aubin. The panel would like to take this opportunity to recognize Dick's lasting contributions to not only the effort of this study, but to the rapid prototyping community at large.

Dick graduated from of the University of Hartford and was employed at Pratt & Whitney (United Technologies, UT) for many years. He led numerous partnership efforts among industry, universities and government. He served as the chairman of the Rapid Prototyping Association of the Society of Manufacturing Engineers and chaired the National Science Foundation's Rapid Mold Tooling Consortia, a venture of MIT, UT and other Fortune 500 companies. He was a pioneer in the International Intelligent Manufacturing Systems (IMS) effort with his work in the Rapid Product Development feasibility study. He leaves an internationally acclaimed reputation for his knowledge and leadership in these advanced manufacturing technologies. At the time of his death he was Manager of Rapid Manufacturing, United Technologies Research Center.

Dick Lopatka, one of Dick's colleagues at United Technologies, speaks for all of us in saying, "Dick will be greatly missed not only due to his technology leadership, but for his energy, humor, generosity and concern for others."

It was an honor to have Dick as a member of this panel. He was an innovative leader, an outstanding educator in the field of rapid prototyping, and an inspiration to those whose lives he touched. He will be missed by all who knew him.

Fritz B. Prinz
Panel Chair

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FOREWORD

The National Science Foundation (NSF) has been involved in funding technology assessments comparing the United States and foreign countries since 1983. A sizable proportion of this activity has been in the Japanese Technology Evaluation Center (JTEC) and World Technology Evaluation Center (WTEC) programs. NSF has supported more than 40 JTEC and WTEC studies over a wide range of technical topics. Both programs are now subsumed under the single name, WTEC, although the JTEC name still appears in some reports that cover only Japan.

As U.S. scientific and technological leadership is challenged in areas of previous dominance such as aeronautics, space, and nuclear power, many governmental and private organizations seek to set policies that will help maintain U.S. strengths. To do this effectively requires an understanding of the relative position of the United States and other countries. The purpose of the WTEC program is to assess research and development efforts in other countries in specific areas of technology, to compare these efforts and their results to U.S. research in the same areas, and to identify opportunities for international collaboration in precompetitive research.

Many U.S. organizations support substantial data gathering and analysis efforts directed at nations such as Japan. But often the results of these studies are not widely available. At the same time, government and privately sponsored studies that are in the public domain tend to be "input" studies; that is, they provide enumeration of inputs to the research and development process, such as monetary expenditures, personnel data, and facilities, but do not provide an assessment of the quality or quantity of the outputs obtained.

Studies of the outputs of the research and development process are more difficult to perform because they require a subjective analysis performed by individuals who are experts in the relevant technical fields. The NSF staff includes professionals with expertise in a wide range of disciplines. These individuals provide the technical expertise needed to assemble panels of experts who can perform competent, unbiased, technical reviews of research and development activities.

Specific technologies, such as telecommunications, biotechnology, microelectromechanical systems, and advanced materials, are selected for study by government agencies that have an interest in obtaining the results of an assessment and are able to contribute to its funding. A typical assessment is sponsored by two to four agencies. In the first few years of the program, most of the studies focused on Japan, reflecting concern over Japan's growing economic prowess.

Beginning in 1990, we began to broaden the geographic focus of the studies. As interest in the European Community (now the European Union) grew, we added Europe as an area of study. With the breakup of the former Soviet Union, we began organizing visits to previously restricted research sites opening up there. These most recent WTEC studies have focused on identifying opportunities for cooperation with researchers and institutes in Russia, the Ukraine, and Belarus, rather than on assessing them from a competitive viewpoint. Most recently, studies have begun to focus also on emerging technological powers in Asia.

In the past several years, we also have begun to substantially expand our efforts to disseminate information. Attendance at WTEC workshops (in which panels present preliminary findings) has increased, especially industry participation. Representatives of U.S. industry now routinely number 50% or more of the total attendance, with a broad cross-section of government and academic representatives making up the remainder. Publications by JTEC and WTEC panel members based on our studies have increased, as have the number of presentations by panelists at professional society meetings.

The WTEC program will continue to evolve in response to changing conditions in the years to come. We are now implementing initiatives aimed at the following objectives:

- Disseminating the results of WTEC studies via the Internet. Fourteen of the most recent WTEC final reports are now available on the World Wide Web (http://itri.loyola.edu) or via anonymous FTP (ftp.wtec.loyola.edu/pub/). Viewgraphs from several recent workshops are also on the Web server.

- Expanding opportunities for the larger science and technology community to help define and organize studies
- Increasing industry sponsorship of JTEC and WTEC studies

The latter two objectives are now being served under the recently inaugurated WTEC Community-Initiated State-of-the-Art Reviews (CISAR) initiative. CISAR provides an opportunity for the U.S. R&D community to suggest and carry out studies that might not otherwise be funded solely at the initiative of the government. For example, WTEC has formed partnerships with university/industry teams, with partial funding from industry, to carry out three CISAR studies, covering the Korean semiconductor industry, electronics final assembly technologies in Pacific Rim countries, and civil infrastructure technologies in Pacific Rim countries, respectively. Several other topics are under consideration. Further information on the CISAR initiative is available on the WTEC WWW server (http://itri.loyola.edu/cisar.htm) or by contacting the WTEC office.

In the end, all government-funded programs must answer the question, How has this investment benefited the nation? A few of the benefits of the WTEC program follow:

- JTEC studies have contributed significantly to U.S. benchmarking of the growing prowess of Japan's technological enterprise. Some have estimated that JTEC has been responsible for over half the major Japanese technology benchmarking studies conducted in the United States in the past decade. JTEC reports have also been widely cited in various competitiveness studies.
- These studies have provided important input to policy makers in federal mission agencies. JTEC and WTEC panel chairs have given special briefings to senior officials of the Department of Energy and Commerce, to the National Aeronautics and Space Administration (NASA) administrator, and to the President's science advisor. Two recent studies on electronic packaging and related electronics manufacturing issues have had a particularly significant impact in this regard. The 1995 JTEC report on electronic manufacturing and packaging in Japan was cited by Secretary of Defense William Perry and Commerce Secretary Ronald Brown in their joint announcement of a $30-40 million government initiative to improve U.S. competitiveness in electronic packaging. The President's Office of Science and Technology Policy and two senior officials at the Department of Commerce have received briefings on a follow-on WTEC study covering electronic manufacturing in other Pacific Rim countries.
- Studies have been of keen interest to U.S. industry, providing managers with a sense of the competitive environment internationally. The director for external technology at a major U.S. high-technology firm recently told us that that he always looks for a relevant WTEC report first when beginning to investigate a technology for his company, because these reports provide a comprehensive understanding that includes R&D, process technology, and some information on commercial developments. The list of corporate users of the WTEC World Wide Web server includes virtually all of the nation's high-technology sector.

Not the least important is the educational benefit of the studies. Since 1983 over 200 scientists and engineers from all walks of life have participated as panelists in the studies. As a result of their experiences, many have changed their viewpoints on the significance and originality of foreign research. Some have also developed lasting relationships and ongoing exchanges of information with their foreign hosts as a result of their participation in these studies.

As we seek to refine the WTEC program in the coming years, improving the methodology and enhancing the impact, program organizers and participants will continue to operate from the same basic premise that has been behind the program from its inception: the United States can benefit from a better understanding of cutting-edge research that is being conducted outside its borders. Improved awareness of international developments can significantly enhance the scope and effectiveness of international collaboration and thus benefit all of the United States' international partners in collaborative research and development efforts.

Paul J. Herer
National Science Foundation
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EXECUTIVE SUMMARY

INTRODUCTION

Mastering the art of rapidly prototyping parts and products is vital for any corporation in the race to launch new products. During the last decade, new methods and tools have emerged to facilitate and accelerate product creation. Physical prototyping, in particular, has gained popularity with the help of a concept called "layered manufacturing" or "solid free form fabrication" (SFF).[1] Although the majority of parts built by layered manufacturing are used for modeling purposes only, layered manufacturing already accounts for almost a half billion dollars of business worldwide and is growing rapidly (Wohlers 1996).

The United States pioneered development and commercialization of layered manufacturing systems; now, significant efforts in this area are underway in Europe and Japan, spurred by the obvious advantages of layered manufacturing's ability to rapidly create physical models regardless of shape complexity. A major research focus is direct manufacture of objects from materials such as metals, ceramics, and plastics that have properties similar to their traditionally manufactured counterparts. In addition, layered manufacturing appears to have the potential to build objects with shape complexity and material variety that previously have been impossible. Composite structures with embedded sensors and integrated circuits or complete functional assemblies are other potentially revolutionary areas of application.

In 1995 the U.S. government, encouraged by the Rapid Prototyping Association of the Society of Manufacturing Engineers (SME), initiated a study administered by the Japanese Technology Evaluation Center/World Technology Evaluation Center (JTEC/WTEC) to assess the capabilities of selected European countries and Japan in developing and implementing layered manufacturing technologies. The approach to this study was three-pronged: first, identify and study key foreign RP technologies and discover important new applications under development; second, evaluate and compare foreign competencies to those in the United States; and third, critically examine related standards.

MAJOR FINDINGS

Following are the major conclusions of JTEC/WTEC's panel of experts concerning the current status of rapid prototyping in Europe and Japan compared to the United States.

1. The United States is ahead in technical innovations, materials, and manufacturing applications of layered manufacturing technology.
2. In the area of machine design, the United States is in parity with Europe and Japan.
3. In rapid prototyping for medical applications, U.S. efforts are distinctly behind those of Europe and Japan.
4. Germany and Japan have implemented major domestic programs to systematically create an infrastructure of strategic RP technologies.

Comparison Chart

Following JTEC/WTEC tradition, the panel attempted to rank the relative strengths of and indicate current trends for several technical SFF categories in Europe, Japan, and the United States, as shown in Table E.1.

[1] Although the term "rapid prototyping" (RP) encompasses more than "layered manufacturing" and "solid freeform fabrication," in this report these terms are used interchangeably.

Rankings like this tend to be controversial. These represent the majority view of the panel but were not necessarily supported unanimously.

Table E.1
Comparisons Between the United States, Japan, and Europe in Rapid Prototyping

TECHNOLOGY	United States	Europe	Japan
Process innovation	XXX	XX	X
Process development	XX	XX	X
Machine design	X	X	X
CAD & interfaces	X	X	
MATERIALS			
Plastics	XX	X	X⇑
Metals	X⇑	X⇑	
Ceramics	X		
APPLICATIONS			
Metal casting	XXX	X⇑	X
Tooling	XXX	XX⇑	X⇑
Medical	X	XXX	XX
INFRASTRUCTURE			
Education	XX	XX	X⇑
Government support for R&D	X	X	X
Industry support for R&D	X	X	X

Key
Xs = relative strength; more Xs = more strength
⇑ = new developments and initiatives pointing to strength in the future

SPECIFIC FINDINGS

Process, Equipment, and Interfaces

- Germany and Japan stress the importance of incremental process and equipment improvement.
- Powder processing for SFF is crucial for a number of process development efforts in the United States and Europe. No layered powder process developments were observed in Japan.
- Investment casting is common in the United States and has driven metal applications of RP. This was found to be true to a lesser extent in Japan and Germany.
- At the time of the panel's visits, neither Germany nor Japan had looked at using SFF technologies beyond numerical control (NC) processing in terms of "opening up the design space." This objective, as is often discussed in the United States, is to take advantage of the enhanced flexibility in manufacturing and materials systems (e.g., the ability to incorporate functionally gradient materials or embedded components) that is facilitated by the SFF layered manufacturing approach.
- R&D efforts in Germany emphasize rapid prototyping of metal structures.

- Several European companies contribute to world RP software infrastructure by focusing on general-purpose software and standards, opening up entrepreneurial software opportunities.
- RP is recognized as a means to maintain Japan's prominence in a variety of industries.
- Representatives of Japanese companies conveyed their strong belief that for RP to be successful, it must be able to compete with NC machining. The importance of high accuracy for SFF parts was stressed frequently in Japan.
- In Japan, accuracy requirements for mass production metal tooling are too high to be met by the resolution of currently available rapid prototyping systems.

Business Environment

- Penetration of three-dimensional (3D) computer-assisted design (CAD) and solid modeling is not as deep in Germany and Japan as in the United States; hence, the acceptance of SFF technologies has occurred at a somewhat slower pace.
- European and Japanese manufacturers do not plan to enter the U.S. market until intellectual property issues are resolved.
- Government coordination in Japan (especially by the Ministry of International Trade and Industry, MITI) is important for driving developments and applications in RP technology.
- Japan does not see a substantial world market for RP products and services yet, but anticipates a growing industry of strategic importance.
- Japan has a long tradition of incremental process improvement. The Japanese RP development effort is in part focused on this strategy.
- Although the U.S. industry is currently ahead, it consists primarily of small companies that are vulnerable to these country-wide organized technology development efforts.

Government Funding for Design and Manufacturing

- Japan has launched a major design and manufacturing program, CALS (Commerce at Light Speed), with a funding level of $300 million for 1996 and an anticipated increase for 1997 and thereafter. This program will have a significant impact on the infrastructure of rapid prototyping technologies.

Education

- Seven Fraunhofer institutes, with financial support from the German government, are cooperating in a rapid prototyping network to speed up the development, advancement, and dissemination of rapid prototyping technologies to improve the competitiveness of the German manufacturing industry.
- Traditionally, manufacturing education in Japan was led by industry. Major changes are envisioned, with universities playing a key role in the education of the next generation of design and manufacturing engineers.
- The Ministry of International Trade and Industry (MITI); the Ministry of Education, Science, and Culture (Monbusho); and Japanese universities are initiating new partnerships promoting collaboration, learning, and joint research.

METHODOLOGY

Details concerning the sponsors, the panelists, and the sites visited by the panel are included in Chapter 1 of this report. Biographies of panelists are contained in Appendix A. The panel visited research and development organizations, government agencies, both users and manufacturers of SFF equipment, and material suppliers in Europe and Japan during October and December of 1995.

REFERENCES

Wohlers, T. 1996. *Rapid prototyping state of the industry: 1995-96 worldwide progress report*. Society of Manufacturing Engineers Symposium, Dearborn, MI (April).

CHAPTER 1

INTRODUCTION

Friedrich B. Prinz

SCOPE OF STUDY

This study reports the findings by a panel of experts on the state of the art in physical rapid prototyping technologies in Europe and Japan. The panel focused its investigation on a new class of rapid prototyping technologies called solid freeform fabrication (SFF).[1] The efforts observed overseas are compared to efforts in the United States. This initiative was sponsored by the U.S. government and administered by the Japan Technology Evaluation Center/World Technology Evaluation Center (JTEC/WTEC) at Loyola College in Maryland. The following agencies supported the study: the National Science Foundation, the Defense Advanced Research Projects Agency, the Office of Naval Research, the Department of Energy, and the Department of Commerce.

It is the mission of this JTEC/WTEC study to inform policymakers, strategic planners, and managers on the state of selected advanced technologies in foreign countries in comparison to the United States.

METHODOLOGY

The expert panel was selected by recommendations from the study chairman and representatives of the sponsoring agencies. The panel was formed of members from industry, academia, and government. Industry members represented primarily users rather than developers of SFF technology. The outcome of this report is based primarily on observations during the site visits. The panel visited 34 sites in subgroups of typically three to five members. All site reports are published as a separate volume, *JTEC/WTEC Panel Report on Rapid Prototyping in Europe and Japan.* Vol. II, *Site Reports* (NTIS report #PB96-199583, September 1996). Site visit reports were reviewed by the host organizations prior to publication.

PANEL MEMBERS

The following experts served as panel members for this study. (Panelists' and other team members' biographies are included in Appendix A.)

[1] Although the term "rapid prototyping" (RP) encompasses more than "layered manufacturing" and "solid freeform fabrication," in this report these terms are used interchangeably.

Industry: Richard F. Aubin, United Technologies Research Center; Robert L. Brown, Gillette Company; and Paul S. Fussell, Aluminum Company of America.

Academia: Fritz Prinz (panel chair), Stanford University; Joe Beaman, University of Texas at Austin; Allan Lightman, University of Dayton; Emanuel Sachs, MIT; and Lee E. Weiss, Carnegie Mellon University.

Government: Clint Atwood, Sandia National Labs; and Michael Wozny, National Institute of Standards and Technology [now at RPI, see Appendix A].

Bruce Kramer and Kesh Narayanan from the National Science Foundation accompanied panelists on site visits. Duane Shelton of JTEC/WTEC and Cecil Uyehara of Uyehara International Associates also traveled with and advised the panel.

APPROACH

The approach to this study was as follows: (1) identify and study key foreign RP technologies and discover important new applications under development; (2) evaluate and compare foreign competencies to those in the United States; and (3) critically examine related standards.

The panel visited research and development organizations, government agencies, and both users and manufacturers of SFF equipment. The panel also visited material suppliers.

SITES VISITED

The group visited sites in Europe during October 25-27, 1995, and sites in Japan during December 11-15, 1995. Tables 1.1 and 1.2 list the sites that the panel visited.

Table 1.1
Sites Visited in Europe

R&D Organizations
Catholic University of Leuven (KU Leuven), Belgium
Fraunhofer Institute for Applied Materials Research (IFAM), Bremen, Germany
Fraunhofer Institute for Production Technology (IPT), Aachen, Germany
Fraunhofer Institute for Manufacturing Engineering and Automation (IPA), Stuttgart, Germany
Institute for Polymer Testing and Polymer Science (IKP), University of Stuttgart, Stuttgart, Germany
Bavarian Laser Center (University of Erlangen), Erlangen, Germany
Fraunhofer Institute for Chemical Technology (ICT), Pfinztal (Berghausen), Germany
Users
Daimler Benz, Sindelfingen, Germany
Manufacturers of SFF Equipment
Fockele and Schwarze, Borchen Alfen, Germany
Cubital, Bad Kreuznach, Germany
Laser 3D/Dassault Aviation, Nancy, France
Electro Optical Systems GmbH, Munich, Germany

Table 1.2
Sites Visited in Japan

R&D Organizations
Hokkaido University (meetings took place in Tokyo)
Osaka Sangyo University, Osaka
Tokyo Metropolitan Institute of Technology, Tokyo
University of Tokyo, Tokyo
Users
Japan Aviation Electronics, Tokyo
Kyoden, Tokyo
Nakamura Pattern Making Co., Aichi
Olympus Optical Co., Yamanashi
Tokuda Industries, Kakamingahara City
Hino Motors, Tokyo
Toyota Motor Corporation, Nagoya
Service Bureaus
INCS, Kanagawa
Shonan Design Co., Tokyo
Manufacturers of SFF equipment
CMET/Asahi Denka, Nagoya
Denken Engineering Co., Oita
D-MEC Ltd., Tokyo
Kira Corp., Kira
Meiko Co., Yamanashi
Omron, Kyoto
Teijin Seiki, Tokyo
Government Organizations
IMS Promotion Center, Tokyo
MITI, Tokyo

REPORT OUTLINE

A brief overview in this chapter on the importance of rapid prototyping technologies is followed by Chapter 2, Process Overview, detailing currently available layered rapid prototyping processes and those under development. Chapter 3, Historical Perspective, gives insights into early developments of layered manufacturing and the evolution of key patents. Chapter 4, Needs, Goals and Objectives, assesses current and future directions of SFF processes and applications. The core of the report consists of Chapters 5-12, which survey materials, software and systems design, machine design, and applications for layered manufacturing in Europe and Japan, with comparisons to work in the United States.

SIGNIFICANCE OF RAPID PROTOTYPING

Introducing new products at ever increasing rates is crucial for remaining successful in a competitive global economy; decreasing product development cycle times and increasing product complexity require new ways to realize innovative ideas. In response to these challenges, industry and academia have invented a spectrum of technologies that help to develop new products and to broaden the number of product alternatives. Examples of these technologies include feature-based design, design for manufacturability analysis, simulation, computational prototyping, and virtual and physical prototyping. Most designers agree that

"getting physical fast" is critical in exploring novel design concepts. The sooner designers experiment with new products, the faster they gain inspiration for further design changes. During the last decade a new physical rapid prototyping concept called layered manufacturing or solid freeform fabrication (SFF) has gained popularity worldwide. The key idea of this new rapid prototyping technology is based on decomposition of 3-D computer models into thin cross-sectional layers, followed by physically forming the layers and stacking them up "layer by layer." Creating 3D objects in a layered fashion is an idea almost as old as human civilization. Constructions as early as the Egyptian pyramids were likely built block by block, layer by layer. Stacking up layers of individually shaped material layers also has a long tradition in a range of manufacturing applications such as tape casting and shape melting.

A little more than a decade ago, the art of building 3D objects by layers was significantly advanced by 3D Systems Inc., a U.S. company based in southern California. Availability of 3D computer models was crucial to realizing the concept of layered object creation, but other technologies such as affordable laser systems, photocurable materials, and powerful personal computers helped to disseminate this technology, called stereolithography. This technology today is capable of producing highly complex 3D geometries with little or no human intervention. Emerging almost in parallel with the advancement of stereolithography were alternative systems for layered manufacturing, offered by a variety of U.S. companies. Included are systems that build layered objects by lamination of sheet materials (Helisys) and by layered fusion or binding of powder articles (DTM, Soligen) or extruded wires (Stratasys). These processes have added a range of new materials that go beyond those of photocurable polymers as used in stereolithography.

Today the key benefits of layered manufacturing are mostly derived from its ability to rapidly create physical models regardless of shape complexity. Also, models built with the help of layered manufacturing processes are valuable during the process of establishing tools for casting and molding.

To further advance U.S. capability in SFF technology, the U.S. government and industry have initiated a range of research projects. The main goal of these efforts is to manufacture "functional components" rather than the "touch and feel" parts that the majority of today's SFF technologies produce. Following the U.S. lead, Europe and Japan have also identified layered manufacturing as a key technology. A number of programs have been initiated in this area. For example, Germany's Fraunhofer Gesellschaft, a nonprofit research organization with more than forty laboratories supported by government and industry, has taken the lead in establishing centers for rapid prototyping research nationwide. Results to date show that innovation and coordination have led to successful transfer of SFF technology into European industries. Similarly, the coordination efforts of Japan's Ministry of International Trade and Industry (MITI) have inspired numerous research and development programs in Japan's industrial laboratories and more recently also in university research settings. [An overview of RP technology and usage based on a study trip to Japan by Marshall Burns can be found in his recent report (Burns 1996).]

In Europe and Japan, educational infrastructure and computational environment have been recognized as key factors for broadening the use of RP in industry. Japan has launched a research and development program called CALS (Commerce at Light Speed) with funding exceeding $300 million in 1996 in order to significantly improve the design and manufacturing infrastructure along a broad range of dimensions, with particular emphasis on computational tools in design and manufacturing. This program is expected to grow during the next few years.

While the United States is still leading the world in most aspects of rapid prototyping, Europe and Japan are catching up fast. Technical innovations in the next few years are likely to dominate this field for more than a decade. The combination of government programs and industrial entrepreneurship will determine who will lead this field in the future.

REFERENCES

Burns, M. 1996. *Fabricators in Japan*. Los Angeles: Ennex Corporation (July).

CHAPTER 2

PROCESSES OVERVIEW

Lee E. Weiss

BACKGROUND

The goal of rapid mechanical prototyping (RP) is to be able to quickly fabricate complex-shaped, three-dimensional parts directly from CAD models. One approach for accomplishing this is to use solid freeform fabrication (SFF) processes. SFF methodologies have the following attributes:

- they can build arbitrarily complex 3D geometries
- the process planning is automatic, based on a CAD model
- they use a generic fabrication machine, i.e., do not require part-specific fixturing or tooling
- they require minimal or no human intervention to operate

Current SFF systems are based upon a layered manufacturing paradigm (Fig. 2.1). In this method, a solid 3D CAD model of the object is first decomposed into cross-sectional layer representations in the process planner. The planner then generates trajectories for guiding material additive processes to physically build up these layers in an automated fabrication machine to form the object. Sacrificial supporting layers are also simultaneously built up to fixture the object. For example, shapes are first decomposed into 2½-dimensional layers, i.e., layers that can be represented by a planar cross-section with an associated uniform thickness.

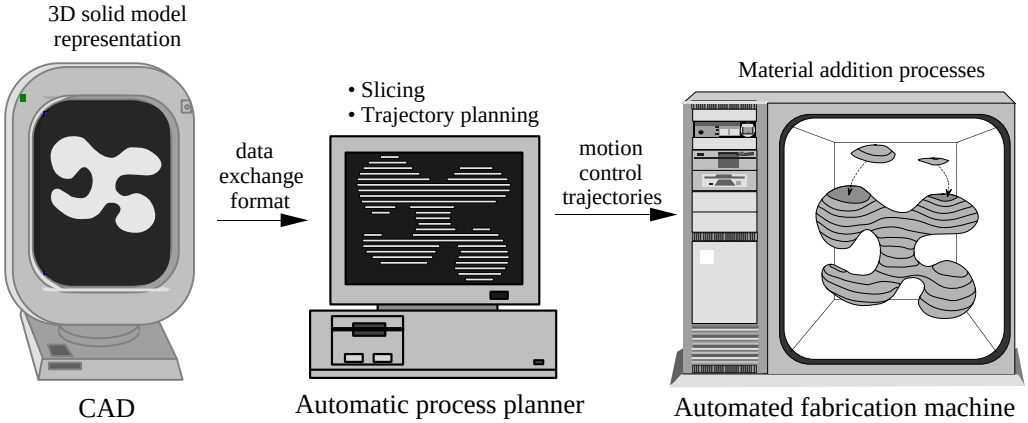
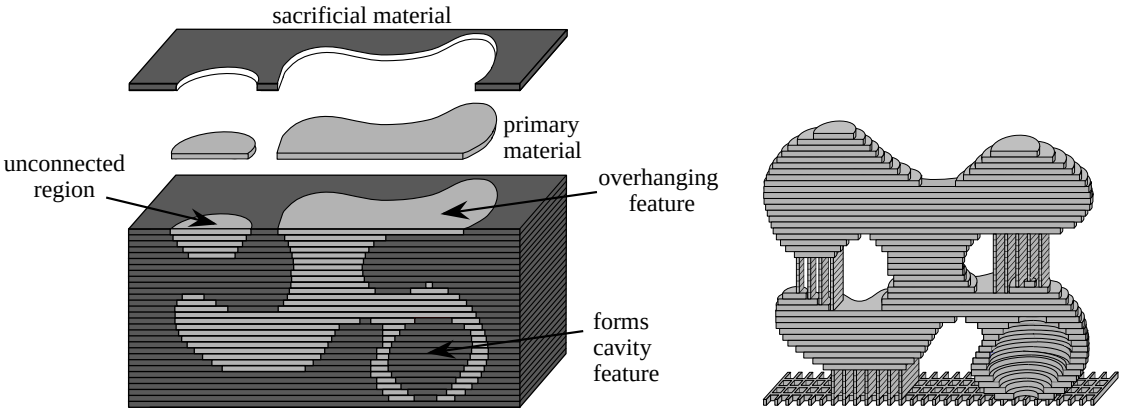


Fig. 2.1. Solid freeform fabrication using a layered manufacturing paradigm.

Each physical layer, which consists of the cross-section and a complementary shaped sacrificial layer, is then deposited and fused to the previous layer (Fig. 2.2a) using one of several available deposition and fusion technologies. The sacrificial material has two primary roles: first, it holds the part, analogous to a "fixture" in traditional fabrication techniques; second, it serves as a substrate upon which "unconnected regions" and overhanging features can be deposited. The unconnected regions require this support since they are not joined with the main body until subsequent layers are deposited. Another use of sacrificial material is to form blind cavities in the part.



a. Complementary support. b. Explicit support.

Fig. 2.2. Generic fixturing.

Other building approaches use support structures only where required, i.e., for the unconnected regions and steep overhanging features (Fig. 2.2b). These explicit support structures are deposited with the same material as the object being formed, but are drawn out in a semisolid fashion so that they are easy to remove once the part is completed. For example, they may be deposited as thin wall structures.

SFF can rapidly and automatically be planned and executed, independent of part shape, for several reasons: (1) the shape decomposition operation maps complex 3D geometry into simple 2½D representations, (2) custom fixturing is not required, and (3) the machinery to implement these systems is relatively easy to operate.

Building up structures in layers is not a new idea; in fact, it goes back to the days of the pyramids — although this was hardly automated construction (Fig. 2.3). Practical implementations of layered manufacturing for modern manufacturing needs have been made possible by several enabling technologies, including CAD-based solids modeling, lasers, ink-jet printing, and high-performance motion controllers, integrated with more traditional manufacturing processes, such as powdered metallurgy, extrusion, welding, CNC (computer numerical control) machining, and lithography, into novel arrangements (Fig. 2.4).

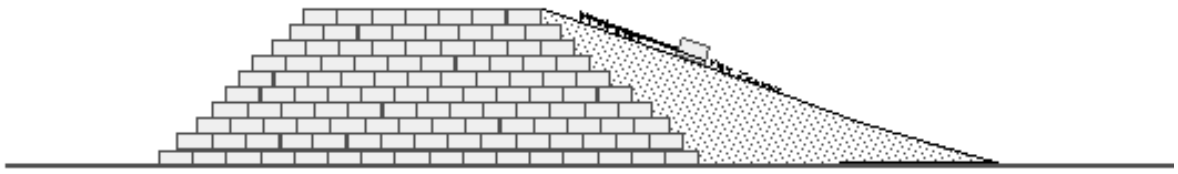


Fig. 2.3. Layered manufacturing of pyramids.

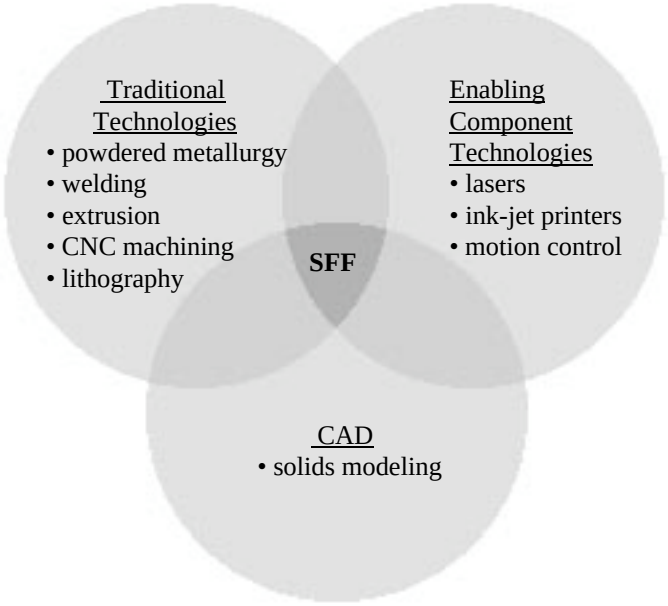


Fig. 2.4. SFF enabling technologies.

Machining also plays an important role in rapid prototyping. CNC machining, however, is not generally considered to be an SFF methodology, not only because it requires skillful human intervention to help plan the operations and to operate the equipment, but also because machining often requires custom fixturing and has inherent geometric limitations. Still, machining can be effective in many rapid prototyping applications. In this JTEC/WTEC mission, the panel visited mostly with researchers and manufacturers of layered manufacturing processes. These processes are described in the next section. The panel also visited with several groups working on machining, and this work is described below in the section on the role of machining in RP.

SFF PROCESSES

The various SFF building strategies and deposition/fusion processes include photolithography, laser fusion, lamination, extrusion, and ink-jet printing. The figures included with the descriptions of these strategies schematically represent these SFF systems. A more detailed description of machine designs, component technologies used to implement each system, and CAD aspects will be presented in following chapters. Table 2.1 summarizes commercialized SFF systems.

Photolithography

Photolithography SFF systems build shapes using light to selectively solidify photocurable resins. There are two basic approaches: laser photolithography and photomasking. The laser photolithography approach depicted in Fig. 2.5, which is currently the most widely used SFF RP technology, was first commercialized by the U.S. company 3D Systems. Not only was 3D Systems the first company to successfully commercialize the stereolithography process, but the company must also be credited with both popularizing RP and establishing a marketplace for RP technologies.

Table 2.1
Commercialized Rapid Prototyping Systems
in the United States, Europe, and Japan

Manufacturer	Process Name	Process Type	Materials
United States			
3D Systems	Stereolithography Apparatus (SLA)	laser photolithography	acrylate, epoxy
Helisys	Laminated Object Manufacturing (LOM)	lamination, laser-cut	paper, tape castings
Stratasys	Fused Deposition Modeling (FDM)	extrusion	ABS, wax, nylon, gel casting
DTM	Selective Laser Sintering (SLS)	power-based, laser fusion	nylon, wax, polycarbonate, polymer-coated metal
Sanders Prototype	Model Maker	liquid jetting	low-melt plastic
Soligen	Direct Shell Production Casting (DSPC)	powder-based, 3D printing of binder	ceramics
BPM	Ballistic Particle Manufacturing (BPM)	liquid jetting	low-melt plastic
3D Systems	Multi-Jet Modeling	liquid jetting	wax
Europe			
EOS (Germany)	STEREOS	laser photolithography	acrylate, epoxy
EOS (Germany)	EOSINT	powder-based, laser fusion	polyamide, polystyrene, metal alloy, resin-coated sand
Cubital [1] (Germany/Israel)	Solid Ground Curing (SGC)	photomasking	acrylate, wax
Fockele & Schwarze (Germany)	LMS	laser photolithography	
Japan			
CMET (NTT Data Communications)	Solid Object Ultraviolet Plotter (SOUP)	laser photolithography	epoxy
D-MEC (JSR/Sony)	Sony's Solid Creation System (SCS)	laser photolithography	urethane acrylate
Kira Corp.	Solid Center	lamination, knife-cut	paper
Teijin Seiki	Solid Forming System (Soliform)	laser photolithography	urethane acrylate, glass-filled resin
Denken Engineering	Solid Laser Plotter (SLP)	laser photolithography	acrylate
Meiko Corp.	Meiko	laser photolithography	acrylate
Mitsui Zosen	COLAMM	laser photolithography	
Ushio, Inc.	Uni-Rapid	laser photolithography	

[1] Cubital is a jointly owned Israeli/German company with headquarters in Israel.

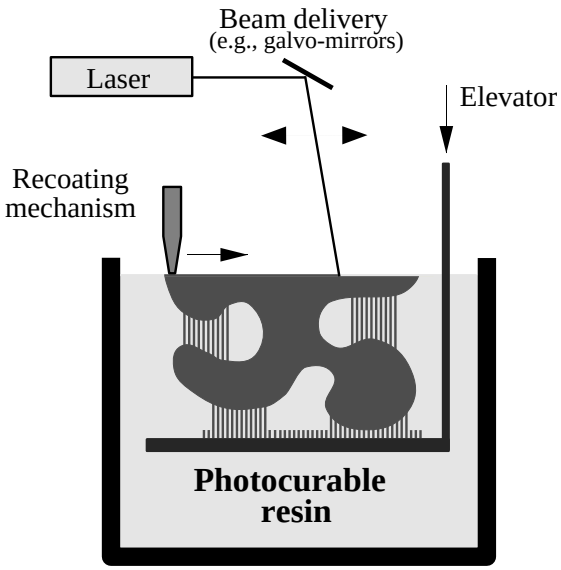


Fig. 2.5. Laser photolithography.

Laser photolithography systems have since been developed and manufactured in both Europe and Japan (Fig. 2.5 and Table 2.2). With the exception of Kira's Solid Center, all RP machines manufactured in Japan are based on laser photolithography. While most laser photolithography systems use the building strategy represented in Fig. 2.5, there are significant differences in machine implementations, particularly in the recoating and beam delivery mechanisms and in the lasers. Chapter 9 describes these implementations in detail.

Table 2.2
Laser Photolithography Systems
in the United States, Europe, and Japan

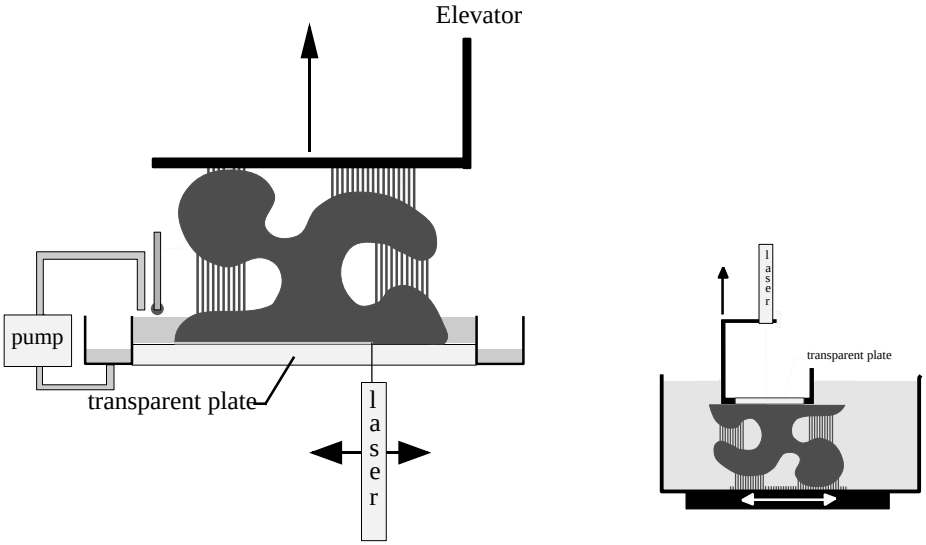
Manufacturer	Process Name
United States	
3D Systems	Stereolithography Apparatus (SLA)
Europe	
EOS (Germany)	STEREOS
Fockele & Schwarze (Germany)	LMS
Laser 3D (France)	Stereophotolithography (SPL)
Japan	
CMET (NTT Data Communications)	SOUP
D-MEC (JSR/Sony)	SCS
Teijin Seiki	Solid Forming System (Soliform)
Denken Engineering	Solid Laser Plotter (SLP)
Meiko Corp.	Meiko
Mitsui Zosen	COLAMM
Ushio, Inc.	Uni-Rapid

Laser photolithography creates acrylic or epoxy parts directly from a vat of liquid photocurable polymer by selectively solidifying the polymer with a scanning laser beam. Parts are built up on an elevator platform that incrementally lowers the part into the vat by the distance of the layer thickness. To build each layer, a laser beam is guided across the surface (by servo-controlled galvanometer mirrors, for example), drawing a cross-sectional pattern in the x-y plane to form a solid section. The platform is then lowered into the vat and the next layer is drawn and adhered to the previous layer. These steps are repeated, layer-by-layer, until the complete part is built up.

Since the photopolymers are relatively viscous, simply lowering the elevator the small distance of the layer thickness (i.e., ~.002 in. to ~.020 in.) down into the vat does not permit the liquid to uniformly recoat the upper surface of the part in a timely fashion. A recoating mechanism is therefore required to facilitate this process. For example, 3D System's stereolithography uses a "deep dipping" recoating, whereby the elevator is first lowered several millimeters so that the liquid entirely flows over the current upper surface of the part. The elevator is then raised to the desired height and a "doctor-blade" (wiper arm) traverses the surface to quickly level the excess viscous material.

With laser photolithography, features with gradually changing overhangs can be built up without support structures. Large overhanging features, however, require supports, since the initial thin layers that form them can warp or break off as the part moves down into the liquid. The supports are typically built up as thin wall sections that can easily be broken away from the part upon completion.

There are a few laser photolithography systems that build using slightly different approaches, such as those depicted in Fig. 2.6. In the machine manufactured by Denken Engineering of Japan shown in Fig. 2.6a, the part is built inverted, attached to a platform that rises up as each successive layer is drawn, and attached to the bottom-most face. The liquid resin layer is deposited on a specially prepared window that is transparent to the laser and to which cured polymer adheres poorly. The platform and prior-built structure are lowered into the resin, leaving between the part and the plate a liquid film having the correct thickness for the next layer. The new layer is drawn from beneath the plate. After the layer is drawn, the new structure is raised, separating the layer from the plate, and the process is repeated until all layers are fabricated. Mitsui Corporation in Japan, which the JTEC/WTEC team did not visit, also manufactures a process, "COLAMM," that scans from below.



a. Solid Laser Plotter
Denken Engineering, Inc. (Japan)

b. Microlithography
Nagoya University

Fig. 2.6. Other laser photolithography approaches.

The process represented in Fig. 2.6b is being developed by Professor Koji Ikuta of Nagoya University and optimized for producing microscale parts — the laser spot size is 5 µm. (The panel did not visit with Prof. Ikuta). In this system a transparent plate is lowered into the vat to form a thin layer of liquid film over the part being built up. The growing part remains stationary in the vat, and the vat is moved relative to a fixed laser beam that passes through the plate, drawing the cross-section. The laser moves up with the plate to maintain precise focusing on the film layer.

In contrast to "drawing out" each cross-section with laser photolithography, it is possible to image an entire cross-section in a single operation using photomasks. This approach was originally developed and commercialized by Cubital (Israel/Germany).[2] The Cubital system, called Solid Ground Curing (SGC), is depicted in Fig. 2.7. In SCG, each cross-section is imaged onto an erasable mask plate produced by charging the plate via an ionographic process and then developing the image with an electrostatic toner (e.g., like the Xerography process). The mask is then positioned over a uniform layer of liquid photopolymer, and an intense pulse of UV light is passed through it to selectively cure the material. Uncured photopolymer is removed from the layer with a vacuum system and replaced with a low-melting-point, water-soluble wax that serves as the sacrificial support. After the wax has cooled, the layer is milled to produce a flat surface. The pattern on the exposed mask is erased by wiping off the toner, and the entire process is repeated. After the part has been completed, the wax is removed by melting. The various processes used to implement SCG are performed at different stations.

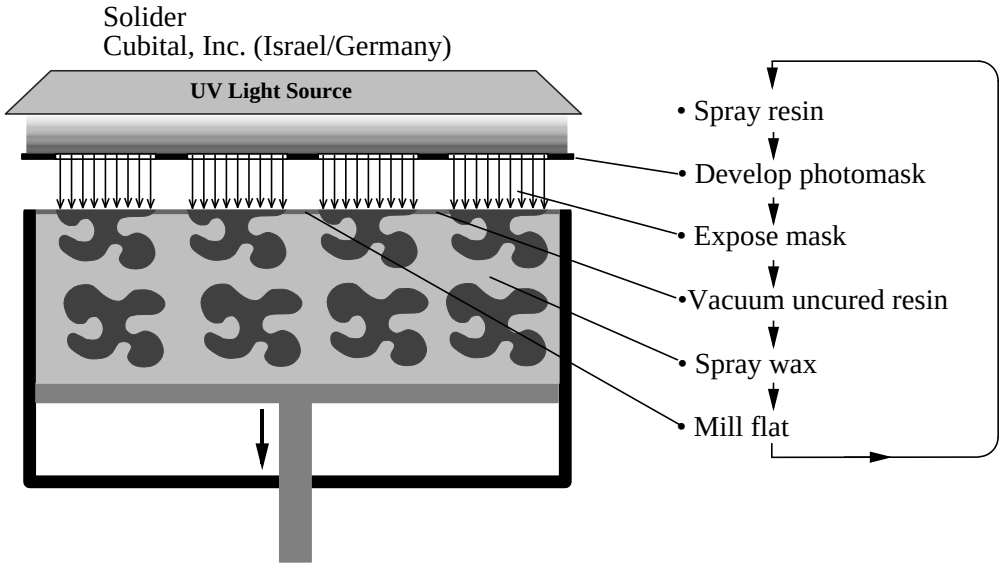


Fig. 2.7. Photomasking.

A unique feature of the photomasking approach is the capability to build multiple parts in a timely fashion in a single batch. Since the building time to form each layer is independent of the part geometry or size, multiple parts (e.g., the four replicates next to each other in Fig. 2.7) can be fabricated in the same time that it normally takes to build a single part. Furthermore, the SGC system builds parts in a solid sacrificial wax material that permits multiple parts to be packed into a single batch (e.g., the two rows of parts shown in Fig. 2.7).

[2] See footnote 1, page 8.

Laser Fusion

Several systems use lasers to selectively fuse powdered material to build up shapes. The "selective laser sintering" approach depicted in Fig. 2.8 was originally developed at the University of Texas at Austin and then commercialized by DTM Corporation (U.S.). EOS, Inc. (Germany), has also developed and marketed its own laser sintering machines. The Fraunhofer Institute for Production Technology (IPT) has also produced an experimental laser-sintering-type unit designed for direct metal sintering.

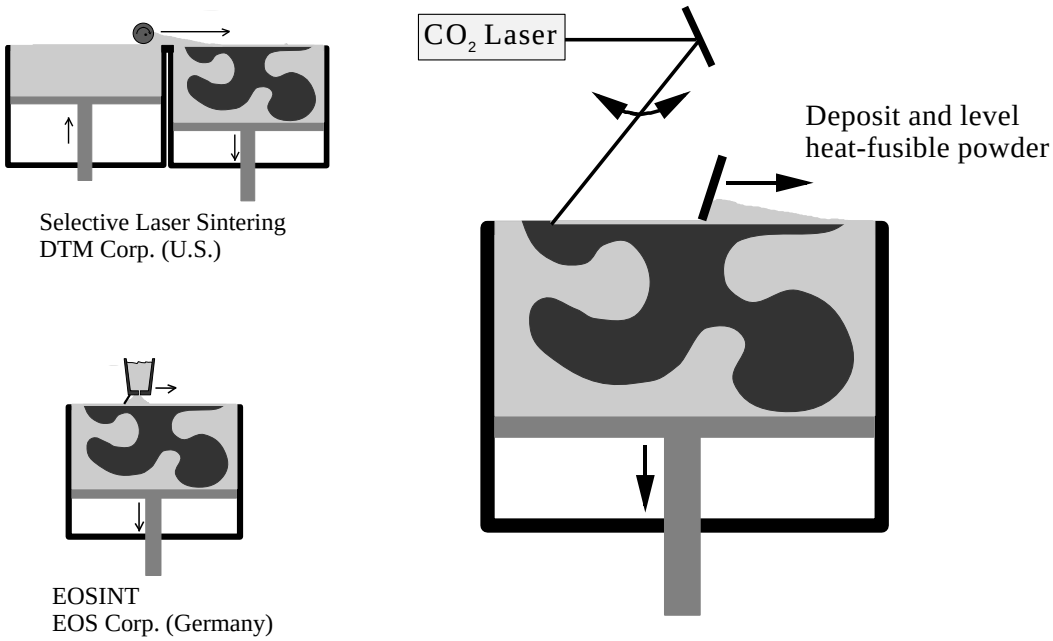


Fig. 2.8. Laser fusion.

In these systems, a layer of powdered material is spread out and leveled over the top surface of the growing structure. A CO_2 laser then selectively scans the layer to fuse those areas defined by the geometry of the cross-section; the laser energy also fuses layers together. The powders are joined by a variety of fusion mechanisms, including melting, surface bonding, sintering aids, and polymer coatings. The unfused material remains in place as the support structure. After each layer is deposited, an elevator platform lowers the part by the thickness of the layer, and the next layer of powder is deposited. When the shape is completely built up, the part is separated from the loose supporting powder. Several types of materials are in use, including plastics, waxes, and low-melting-temperature metal alloys, as well as polymer coated metals and ceramics for making "green" preforms. Direct fusing of metals and ceramics (i.e., uncoated powders) is also being investigated.

While both the DTM and EOS machines are based on the same underlying methodology, there are significant differences in machine implementations, including their respective material delivery approaches. The DTM machine delivers powder from a cylinder adjacent to a second cylinder in which the part is grown; a roller is used to spread and level the powder. In the EOS system, powder spreading is through a slit nozzle whose leading and trailing edges are contoured as the head is vibrated from side to side.

Lamination

There are currently two commercialized SFF lamination systems. Laminated Object Manufacturing (LOM) is a lamination method that was developed and commercialized by Helisys Corporation (U.S.). LOM builds shapes with layers of paper or plastic (Fig. 2.9a). The laminates, which have a thermally activated adhesive, are glued to the previous layer with a heated roller. A laser cuts the outline of the part cross-section for each layer. The laser then scribes the remaining material in each layer into a cross-hatch pattern of small squares (see insert in Fig. 2.9), and as the process repeats, the cross-hatches build up into tiles of support structure. The cross-hatching facilitates removal of this tiled structure when the part is completed. LOM builds up large parts relatively rapidly because only contours are scanned. LOM is also being investigated by Helisys and the University of Dayton for building up ceramic and reinforced composite shapes using layers of "green" tape castings (i.e., sheets of bound powder); the final part must subsequently be sintered.

The only nonphotolithographic SFF system being produced in Japan is a lamination system manufactured by Kira Corporation. While Kira's basic building approach is the same as that used for the Helisys LOM machine, the Kira Solid Center (SC) machine (Fig. 2.9b) is implemented in a significantly different manner. The SC machine uses standard printing paper that is fed into the machine using a conventional laser printer. The printer uses an adhesive-based toner to print the outline of the cross-section as well as a cross-hatched bonding pattern on each piece of paper. A hot plate then laminates the paper to the previous layers. The cross-sectional outline is then cut with a carbide knife that is mounted on a swivel base. Additional segments of "parting-plane" sections are also cut to facilitate removal of the support material.

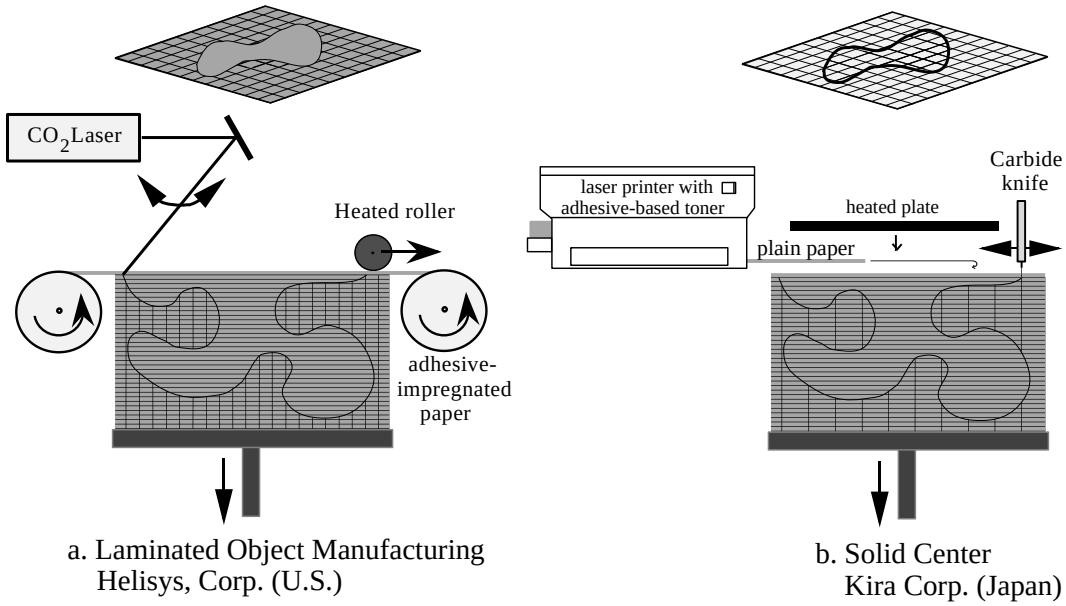


Fig. 2.9. Lamination systems.

Internal cavities are hard to form with the lamination systems described above, since it is difficult to remove the sacrificial material from the internal regions. To address this issue, Case Western Reserve University and CAMLEM, Inc. (U.S.), are developing a lamination system using green tape castings with a separate supporting material fugitive tape. Each section is individually cut with a laser and then stacked in place. The fugitive tape is then burned out during the final firing process.

Extrusion

Extruding freeform shapes was first developed and commercialized by Stratasys, Inc. (U.S.). This approach, called Fused Deposition Modeling (FDM), deposits a continuous filament of a thermoplastic polymer or wax through a resistively heated nozzle (Fig. 2.10, top left). The material is delivered as a wire into the extrusion head and heated to slightly above its flow point so that it solidifies relatively quickly after it exits the nozzle. It is possible to form short overhanging features without the need for explicit support; in general, however, explicit supports are needed. These are drawn out as thin wall sections that can easily be removed upon completion. Various U.S. investigators, including Rutgers University, Allied-Signal, Lone Peak Engineering, and Advanced Ceramics Research, are also exploring the use of FDM with thermoplastic wires and rods loaded with ceramic powders to build "green" preforms.

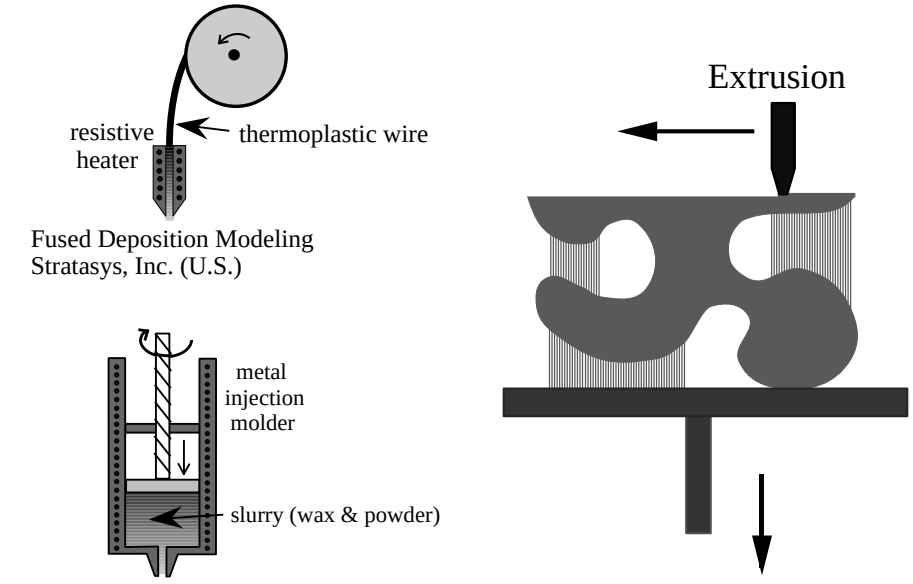


Fig. 2.10. Extruding freeform shapes.

Multiphase Jet Solidification (MJS) is another extrusion-based process (Fig. 2.10, bottom left). MJS is being jointly developed by the Fraunhofer Institutes for Applied Materials Research (IFAM, Bremen) and Manufacturing Engineering and Automation (IPA, Stuttgart). IPA is working on software development and IFAM on material aspects. MJS extrudes metal or ceramic slurries using metal injection molding technology. The slurry, which is about a 50/50 mixture of wax and metal or ceramic powder, is contained in a heated vessel and pumped through an attached nozzle with a screw-activated plunger. The JTEC/WTEC team's hosts at IPA mentioned that commercialization may be through Fockele and Schwarze. The Fraunhofer Institutes have a German patent for MJS and are applying for a U.S. patent. The basic methodology of depositing 3D shapes by extrusion, in layers, is considered to be public domain. The Fraunhofer patent pertains to the feedstock (slurry composition), the heated material supply (up to 200ºC to liquefy the binder and obtain the desired viscosity), and the extrusion nozzle.

Ink-Jet Printing

Several SFF processes have taken advantage of ink-jet printing technology to print layers of structures. The first process that successfully demonstrated "printing" of shapes was the Three-dimensional Printing (3DP)

process, depicted in Fig. 2.11a, which was developed at MIT as a method to form "green" preforms for powdered metallurgy applications. While different powdered materials can be used, 3DP is currently commercialized by Soligen Corporation (U.S.) under the name Direct Shell Production Casting (DSPC) for creating ceramic shells and cores for casting applications. In 3DP, the part is built up in a bin that is fitted with a piston to incrementally lower the part into the bin. Powder (such as alumina) is dispensed from a hopper above the bin, and a roller is used to spread and level the powder. An ink-jet printing head scans the powder surface and selectively injects a binder (such as colloidal silica) into the powder. The binder joins the powder together into those areas defined by the geometry of the cross-section. The unbound powder becomes the support material. When the shape is completely built up, the "green" structure is fired, and then the part is removed from the unbound powder. 3DP of metal powders, such as stainless steel bound with a polymeric binder, is also being explored; subsequent infiltration of the matrix is then required for densification.

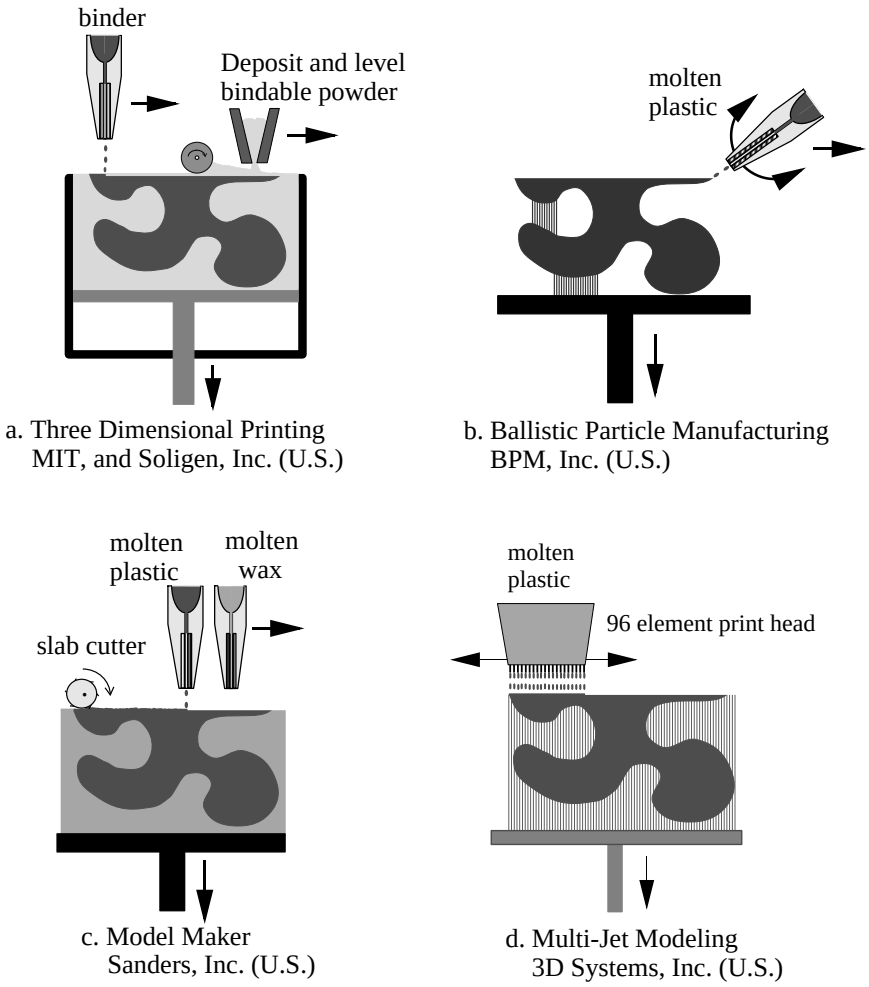


Fig. 2.11. Ink-jet printing systems.

Other processes use ink jets to directly deposit low-melting target materials. Ballistic Particle Manufacturing (BPM), which was developed and commercialized by BPM Technology, Inc. (U.S.), uses a piezoelectric jetting system to deposit microscopic particles of molten thermoplastic (Fig. 2.11b). Like FDM and SLA, support structures are required for "unconnected" features. The supports are deposited in a perforated pattern to facilitate removal. The BPM jet head, however, is mounted on a 5-axis positioning mechanism so that overhanging features can be deposited without support, as the figure shows.

The Model Maker system (Fig. 2.11c) of Sander's, Inc. (U.S.), dispenses both a low-melting-temperature thermoplastic and a separate wax support material. In addition, it incorporates a slab cutter to plane each layer to the precise thickness.

In other commercial developments, 3D Systems, Inc. (U.S.), has just introduced a new ink-jet prototyping system, "Multi-Jet Modeling," (Fig. 2.11d), which uses a printing head with 96 individual jets that deposits a low-melting-temperature thermoplastic. Using the same material the support structure is deposited as thin, needle-like structures.

In other research efforts, the Technical University of Munich (not visited by the panel) is developing a "modified" three-dimensional printing process that injects streams of UV-curable binder resins under a UV light. Also, investigators at MIT and the University of California, Irvine, are developing jetting systems to deposit metal alloys.

ROLE OF MACHINING IN RP

The main competition to SFF-based rapid prototyping systems is NC (numerical control) machining, used typically in small model-making shops. In comparison with current SFF processes, machining can produce parts with superior accuracy and surface finish and having a much broader range of materials, especially tooling steels. Furthermore, if only 2D drawings are available, then machining by a skilled model maker can often be executed more quickly than the time it takes to first create the 3D model required for SFF processing. Machining, therefore, remains strategically important to industry in both Europe and Japan, due in part to the relatively slow dissemination of 3D CAD in both areas. There are also concerns about the inability of current SFF processes to (1) produce parts with the accuracy and surface finish required for many engineering models, (2) build with a wide variety of engineering materials, and (3) directly produce high-quality metal parts for production tooling applications.

Completely automated CNC machining would have a significant impact on rapid prototyping. Current CNC systems, however, are not generally considered to be SFF technologies for the following reasons: they still require skillful human intervention to help plan the operations and to operate the equipment; custom fixturing and special tooling is often required; and machining has inherent geometric limitations (Fig. 2.12). However, just as SFF process performance capabilities are expected to improve, automated CNC planning capabilities are also expected to continue to improve with the proliferation of 3D CAD modeling systems. In the future, both CNC and SFF will remain important technologies for RP needs.

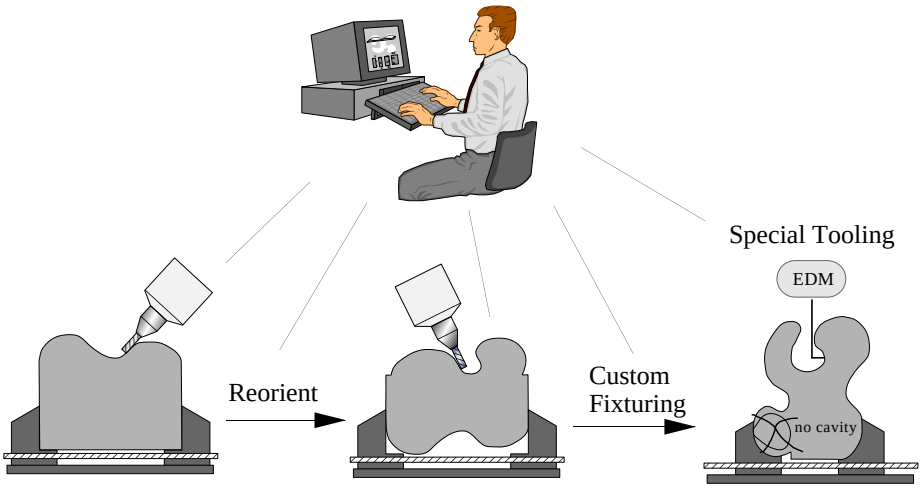


Fig. 2.12. Why isn't CNC machining an SFF process?

Material Removal Processes

While improving the capabilities of automated CNC planning systems is important, there is also a need to improve the machining processes themselves. There is interesting work in both Germany and Japan on machining and other material removal processes. The main application area for these processes is in rapid tool manufacturing. Tooling fabrication relaxes some geometry constraints; for example, undercut features are not normally required.

Lasercaving, which process is used by LCTec, Inc. (Germany), is being refined by the Bavarian Laser Center (BLZ). It is a material removal process used to cut cavities into metal or ceramic stock in a downward, layer-by-layer fashion. A high-power laser and oxygen source are simultaneously directed at the surface to be cut and swept across the cutting path. The heated metal oxidizes, and oxidized chips break away due to differential thermal expansion between the underlying unoxidized material and the oxide fragment (Fig. 2.13).

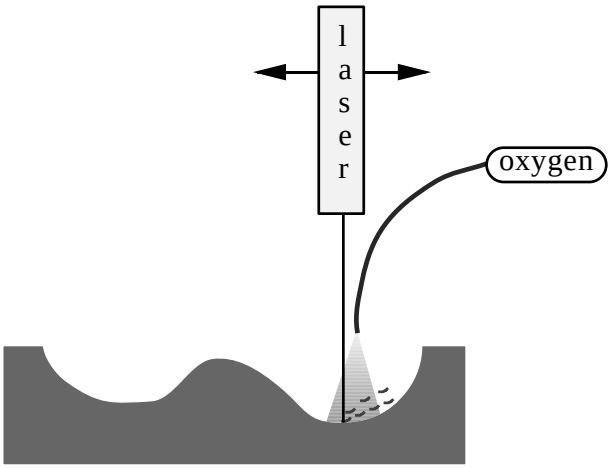


Fig. 2.13. Lasercaving.

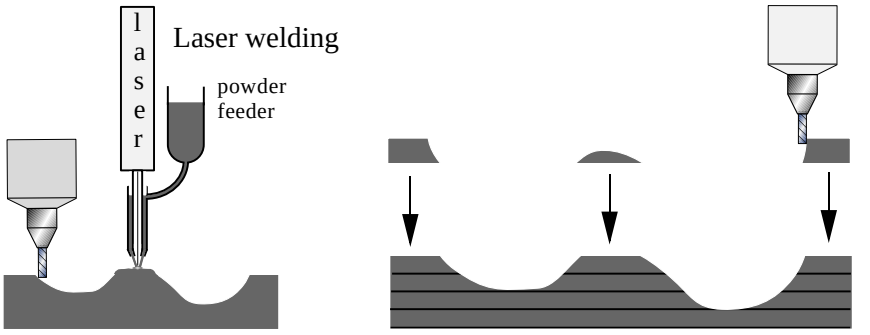
The system includes a 5-axis CNC vertical milling machine and a 750 W CO_2 laser. Parts are mounted on the mill and moved relative to the fixed beam. The claimed accuracy is 0.05 mm, and the material removal rate is 5 mm^3/min. Overall machining times can be reduced by first roughing out material at a higher rate using the laser in a melting mode that removes material at a rate of 1,000 mm^3/min. Surface roughness is about 5 µm. Primary applications BLZ is exploring are cutting cavities in tools and texturing tooling surfaces.

The JTEC/WTEC team saw examples of steel dies and leather-like textured patterns; their surface quality was excellent. These surfaces must be glass-beaded to remove oxidation; otherwise, no additional processing is required. Lasercaving can be a powerful method for building and texturing tools with fine detail and small features. In Japan, Professor Nakagawa of Tokyo University has extensive leading-edge research in the use of high-speed machining, i.e., spindle speeds of ~100,000 RPM. He is particularly interested in the use of high-speed machining for rapid tooling manufacturing.

Processes That Combine Material Addition and Removal

There are also efforts to investigate combining the benefits of material additive processes (especially that they simplify planning) with the benefits of material removal processes (that their accuracy and surface finish are superior). The primary application area has been for tooling manufacturing. The Fraunhofer IPT has developed an experimental system, called "Laser Generated RP," which uses laser welding to melt metal powder as it drops from a coaxial laser/powder distribution cone (Fig. 2.14a). Other concentric cones within the probe deliver shroud gas and fluids for cooling. The system uses either a 900 W CO_2 laser or a 1,000 W

Nd:YAG laser. Within the work chamber is a 2½D milling cutter to finish the walls of the metal part and improve tolerances. IPT representatives claim that this unit produces full-density parts, but they did not disclose their deposition and cutting strategies to the JTEC/WTEC team. They showed the team both thin wall and solid parts made of steel from this experimental unit. IPT plans to commercially develop this system with a die casting machine tool company over the next few years. With significant funding from its commercial partner, chances of commercializing this technique appear promising.



a. Laser Generated RP
Fraunhofer IPT (Germany)

b. Large-scale lamination
Professor Nakagawa, Tokyo University

Fig. 2.14. Combining material addition with material removal.

In addition to his work in high-speed machining, Professor Nakagawa is developing lamination processes to build up large-scale tooling, such as forming dies for automobile bodies. Individual sections of material are shaped with CNC cutting and then stacked up to form the tool (Fig. 2.14b). However, neither the method of registration nor the joining process was disclosed to the team.

The addition/removal processes described above apparently do not incorporate support structures. Carnegie Mellon and Stanford universities are developing an addition/removal process, Shape Deposition Manufacturing (SDM), which does incorporate support structures. In SDM, a CAD model is first sliced into 3D layered structures (i.e., the outer surface of each layer maintains the 3D geometry of the original model). Layer segments are then deposited as near-net shapes and then machined to net shape before additional material is deposited (Fig. 2.15). The sequence for depositing and shaping the primary and support materials is dependent upon the local geometry; the idea is to decompose shapes into layer segments such that undercut features need not be machined, but are formed by previously shaped segments.

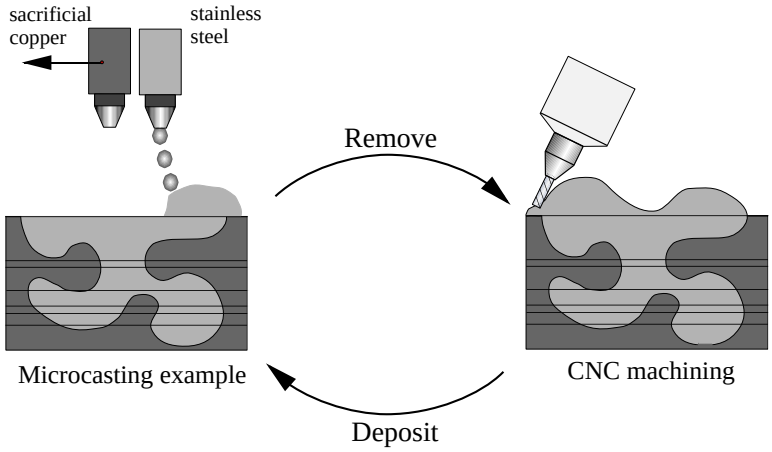


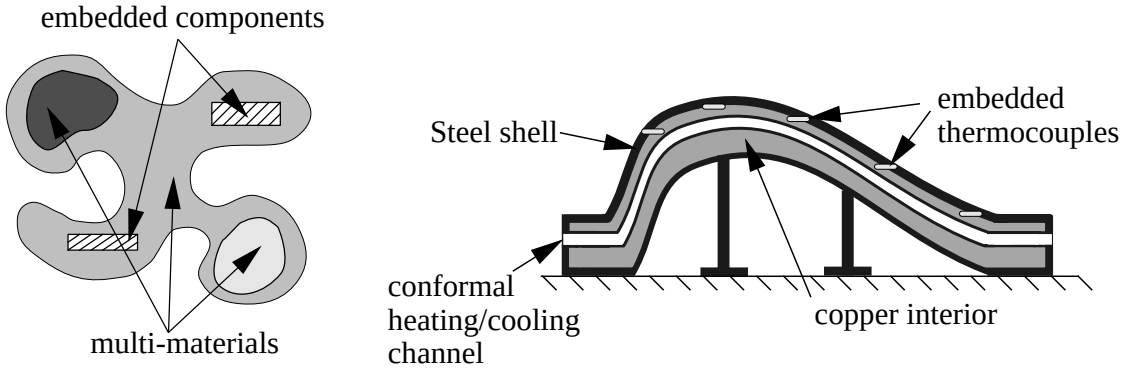
Fig. 2.15. Shape deposition manufacturing.

SDM can use alternative deposition sources. For one example, microcasting is a nontransferred welding process that deposits discrete, super-heated molten metal droplets in order to build up fully dense, metallurgically bonded structures. For example, stainless steel may be deposited as the primary material and copper as the sacrificial material. Other types of deposition processes being investigated include laser welding, extrusion, and 2-part epoxy mixtures.

CONCLUSIONS

- The United States appears to be ahead in SFF technological innovations, while Japan and Europe focus on process improvements. However, these issues are currently the subjects of heated patent debates.
- Which is the best RP process is dependent on the application and is a function of several factors and constraints, including cost, building speed, accuracy, operating environment (e.g., office vs. shop floor), and material type and properties. The end-user must judge.
- While SFF processes will continue to evolve, it appears that improved machining processes and automated CNC planning also will continue to play important roles in rapid prototyping.
- To date, the most widely recognized advantage of layered manufacturing methodology is the relative ease of automatically planning and executing the fabrication of complex geometric shapes. Building shapes using selective material deposition and/or fusion processes, however, might have a second, far-reaching advantage: it will also be possible to create heterogeneous structures, as depicted in Fig. 2.16a. A heterogeneous structure might include multimaterial regions and/or prefabricated devices embedded into the growing shapes and surfaces with microgeometric textures. These types of designs would not be practical, perhaps might be impossible, to fabricate with conventional forming techniques. While this use of SFF is being investigated in the United States, the JTEC/WTEC panel saw no evidence that either the Japanese or Germans have been exploring these possibilities.

  One example of a heterogeneous structure is the forming tool depicted in Fig. 2.16b. This tool would include a conformally shaped heating/cooling channel, formed with sacrificial material. The tool's interior would be made of copper for fast and uniform heating or cooling; its outside shell would be made of steel for strength. Its thermal mass would be minimized by a geometry that minimizes tool volume. Arrays of embedded thermocouples would permit the tool's surface temperature to be monitored for process control.



a. Heterogeneous structure. b. Complex tooling.

Fig. 2.16. In the future, SFF will enable complex designs.

CHAPTER 3

HISTORICAL PERSPECTIVE

Joseph J. Beaman

TECHNOLOGY

The early roots of rapid mechanical prototyping technology can be traced to at least two technical areas: topography and photosculpture.

Topography

As early as 1890, Blanther (1892) suggested a layered method for making a mold for topographical relief maps. The method consists of impressing topographical contour lines on a series of wax plates, cutting the wax plates on the contour lines, and then stacking and smoothing the wax sections. This produces both positive and negative three-dimensional surfaces that correspond to the terrain indicated by the contour lines. After suitable backing of these surfaces, a printed paper map is then pressed between the positive and negative forms to create a raised relief map. This is shown in Fig. 3.1.

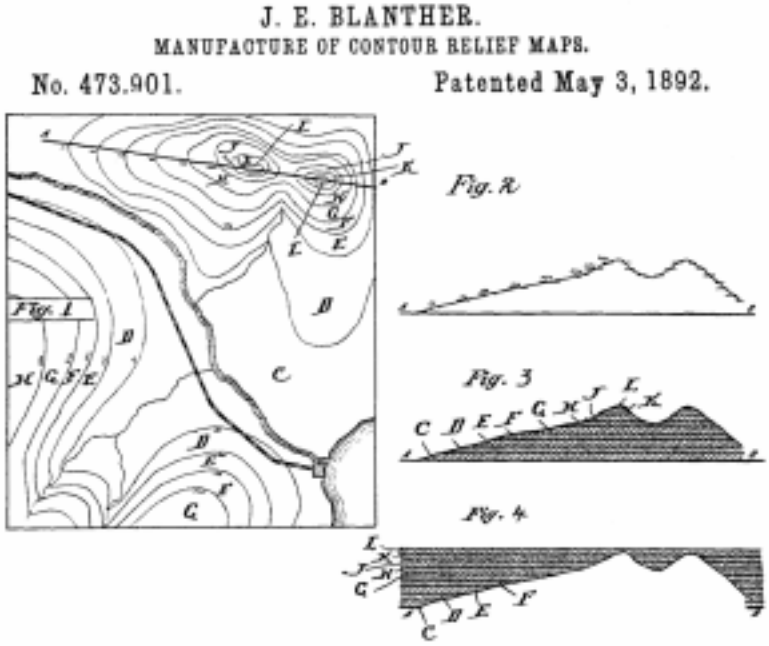


Fig. 3.1. Layered mold relief map proposed by Blanther (1892).

Perera (1940) proposed a similar method for making a relief map by cutting contour lines on cardboard sheets and then stacking and pasting these sheets to form a three-dimensional map. Further refinements of this approach were made by Zang (1964), who suggested using transparent plates with topographical detail inscribed on each plate, and Gaskin (1973), who described a three-dimensional geological teaching device. In 1972, Matsubara of Mitsubishi Motors (1974) proposed a topographical process that uses photo-hardening materials. In this process, a photopolymer resin is coated onto refractory particles (e.g., graphite powder or sand), which are then spread into a layer and heated to form a coherent sheet. Light (e.g., from a mercury vapor lamp) is selectively projected or scanned onto this sheet to harden a defined portion of it. The unscanned, unhardened portion is dissolved away by a solvent. The thin layers formed in this way are subsequently stacked together to form a casting mold. In 1974, DiMatteo (1976) recognized that these same stacking techniques could be used to produce surfaces that are particularly difficult to fabricate by standard machining operations. Examples he mentions include propellers, air foils, three-dimensional cams, and forming of dies for punch presses. In one embodiment (Fig. 3.2), contoured metallic sheets are formed by a milling cutter, then joined in layered fashion by adhesion, bolts, or tapered rods. This process has obvious similarity to the earlier 19th century work.

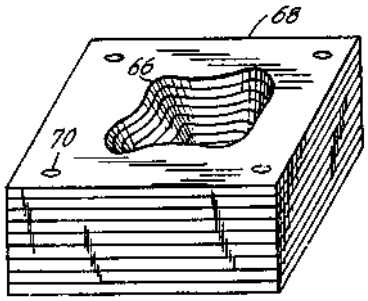


Fig. 3.2. Layered mold of stacked sheets by DiMatteo (1974).

In 1979, Professor Nakagawa of Tokyo University began to use lamination techniques to produce actual tools such as blanking tools (Nakagawa et al. 1979), press forming tools (Kunieda and Nakagawa 1984), and injection molding tools (Nakagawa, Kunieda, and Liu 1985). Of particular note, Nakagawa mentions the possibility of complex cooling channels in injection molds (Nakagawa, Kunieda, and Liu 1985).

Photosculpture

Photosculpture arose in the 19th century in attempts to create exact three-dimensional replicas of objects, including human forms (Bogart 1979). One somewhat successful realization of this technology was designed by Frenchman François Willème in 1860. In his method, shown in Fig. 3.3, a subject or object was placed in a circular room and simultaneously photographed by 24 cameras placed equally about the circumference of the room. The silhouette of each photograph was then used by an artisan in Willème's studio (Fig. 3.4) to carve out 1/24th of a cylindrical portion of the figure.

In an attempt to alleviate the labor-intensive carving step of Willème's photosculpture, Baese (1904) described a technique using graduated light to expose photosensitive gelatin, which expands in proportion to exposure when treated with water. Annular rings of the treated gelatin are then fixed on a support to make a replica of an object, as shown in Fig. 3.5. Similar techniques and improvements were developed by Monteah (1924).

In some of the earliest work in Japan, Morioka (1935, 1944) developed a hybrid process combining aspects of photosculpture and topography. This method (Fig. 3.6) uses structured light (black and white bands of light) to photographically create contour lines of an object. The lines can then be developed into sheets and cut and stacked, or projected onto stock material for carving.

Fig. 3.3. Admiral Farragut sits, late 1860s, for photosculpture (Bogart 1979; photo courtesy of George Eastman House).

Fig. 3.4. François Willème's photosculpturing studio in Paris, about 1870 (Bogart 1979; photo courtesy of George Eastman House).

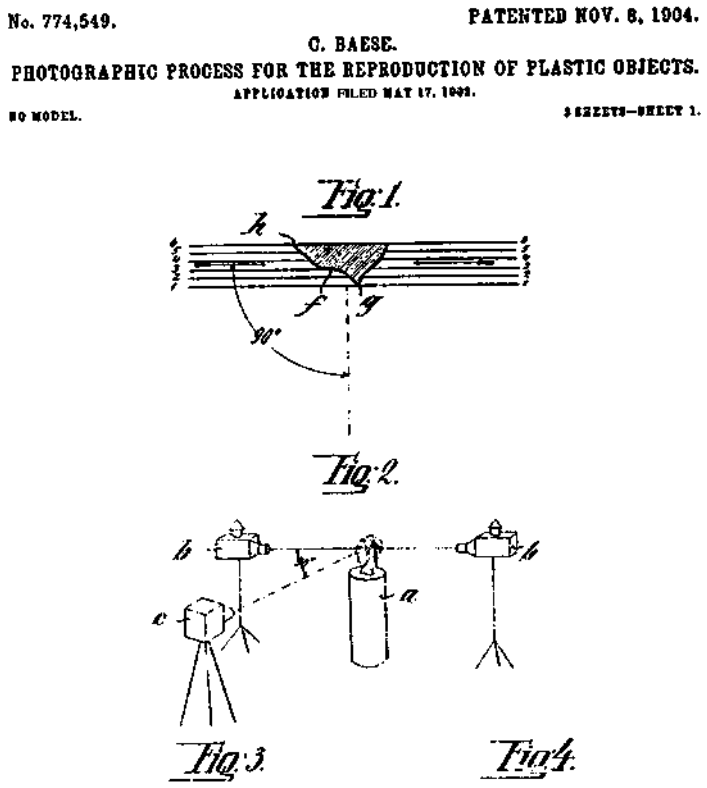


Fig. 3.5. Photographic process for the development of plastic objects by Baese (1904).

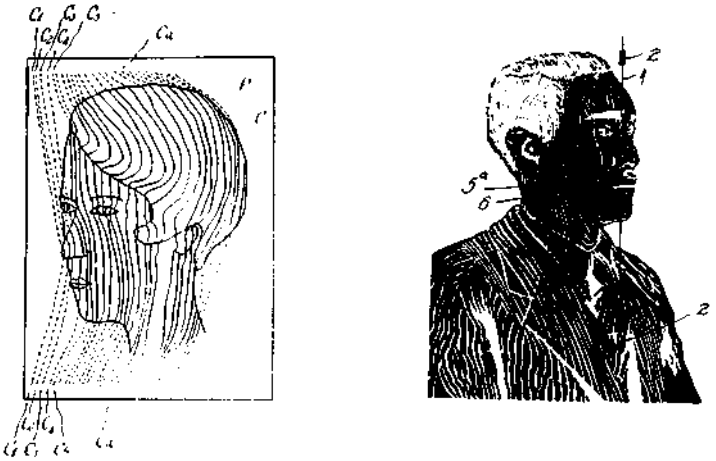


Fig 3.6. Process for manufacturing a relief by Morioka (Morioka 1935, 1944).

In 1951, Munz (1956) proposed a system that has features of current stereolithography techniques (Fig. 3.7). He disclosed a system for selectively exposing a transparent photo emulsion in a layerwise fashion, where each layer comes from a cross-section of a scanned object. These layers are created by lowering a piston in a cylinder and adding appropriate amounts of photo emulsion and fixing agent. After exposing and fixing, the resulting solid transparent cylinder contains an image of the object. Subsequently this object can be manually carved or photochemically etched out to create a three-dimensional object.

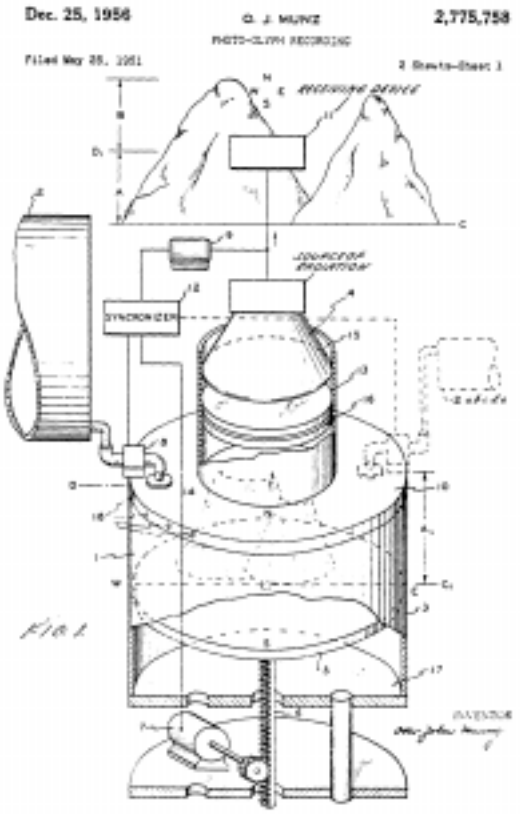


Fig. 3.7. Process by Munz (1956) to reproduce a three-dimensional image of an object.

Early Solid Freeform Fabrication

In 1968, Swainson (1977) proposed a process to directly fabricate a plastic pattern by selective three-dimensional polymerization of a photosensitive polymer at the intersection of two laser beams. Parallel work was conducted at Battelle Laboratories (Schwerzel 1984). The essential features of this process, termed photochemical machining, are depicted in Fig. 3.8. The object is formed by either photochemically cross-linking or degrading a polymer by simultaneous exposure to intersecting laser beams. Although laboratory hardware was constructed for this process, a commercially viable process was apparently not achieved.

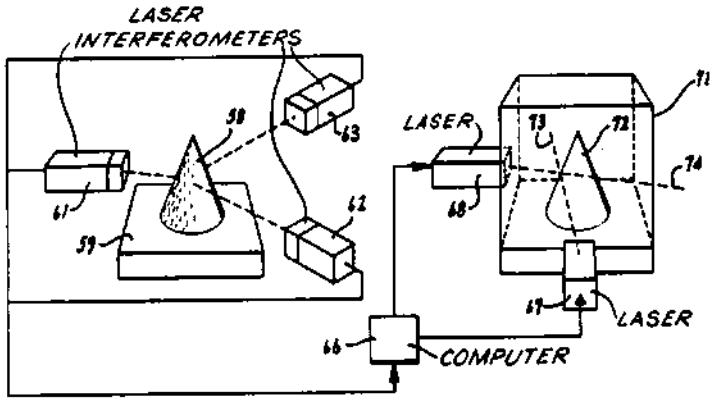


Fig. 3.8. Photosculpture process using intersecting laser beams, by Swainson (1977).

A powder process that has more in common with laser surface cladding techniques than photosculpture was proposed in 1971 by Ciraud (1972). This disclosure describes a process for the manufacture of objects from a variety of materials that are at least partially meltable. In order to produce an object, small particles are applied to a matrix by gravity, magnetostatics, or electrostatics, or positioned by a nozzle located near the matrix. The particles are then heated locally by a laser, electron beam, or plasma beam. As a consequence of heating, the particles adhere to each other to form a continuous layer. As Fig. 3.9 shows, more than one laser beam can be used in order to increase the strength of the union between the particles.

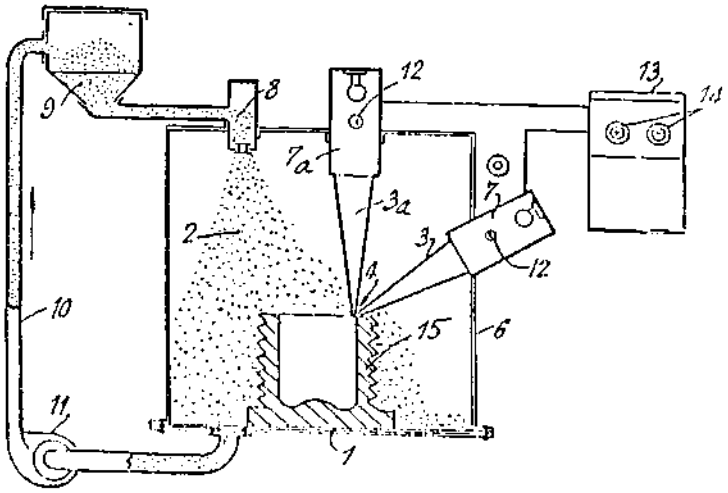


Fig. 3.9. Powder laser process proposed by Ciraud (1972).

Hideo Kodama of Nagoya Municipal Industrial Research Institute was the first to publish an account of a functional photopolymer rapid prototyping system (Kodama 1981). In his method, a solid model is fabricated by building up a part in layers, where exposed areas correspond to a cross-section in the model. He studied three different methods for achieving this (Fig. 3.10):

a. using a mask to control exposure of the UV source and immersing the model downward into a liquid photopolymer vat in order to create new layers
b. using a mask as in (a), but positioning the mask and exposure on the bottom of the vat and drawing the model upward to create a new layer
c. immersing the model as in (a), but using an x-y plotter and an optical fiber to expose the new layer

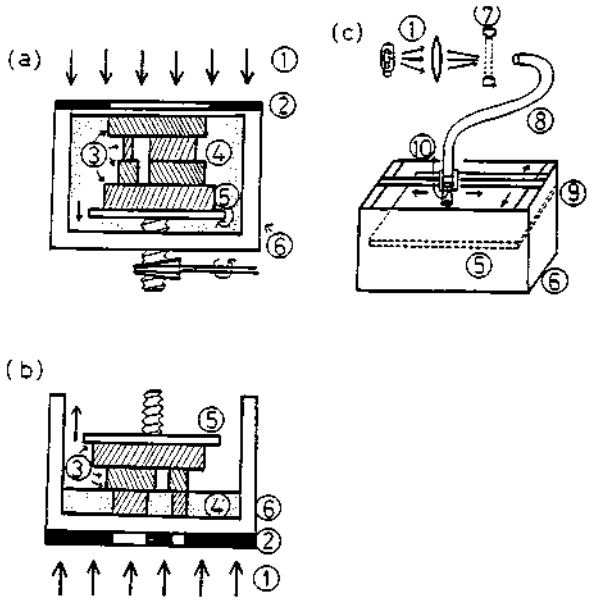


Fig. 3.10. Schematics of three photopolymer systems studied by Kodama (1981).

A second, parallel but independent, effort was conducted by Herbert at 3M Corporation (1982). Herbert describes a system that directs a UV laser beam to a photopolymer layer by means of a mirror system on an x-y plotter (Fig. 3.11). In Herbert's experimental technique, a computer is used to command a laser beam across a layer, the photopolymer vessel is then lowered (~ 1 mm), and additional liquid photopolymer is then added to create a new layer.

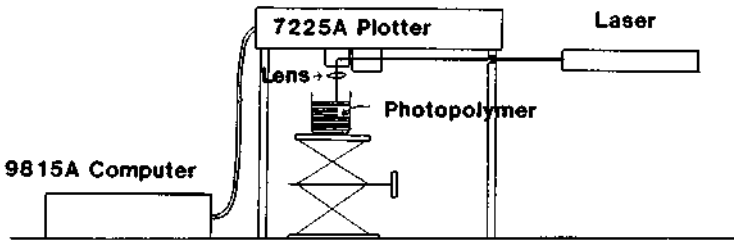


Fig. 3.11. Herbert's photopolymer process (1982).

Active Patents

Besides those described above, there are numerous active patents that cover existing commercial processes. Table 3.1 lists the most prominent patents.

Table 3.1
Active Rapid Prototyping Patents

NAME	TITLE	FILED	COUNTRY
Housholder	Molding process	December 1979	U.S.
Murutani	Optical molding method	May 1984	Japan
Masters	Computer automated manufacturing process and system	July 1984	U.S.
André et al.	Apparatus for making a model of an industrial part	July 1984	France
Hull	Apparatus for making three-dimensional objects by stereolithography	August 1984	U.S.
Pomerantz et al.	Three-dimensional mapping and modelling apparatus	June 1986	Israel
Feygin	Apparatus and method for forming an integral object from laminations	June 1986	U.S.
Deckard	Method and apparatus for producing parts by selective sintering	October 1986	U.S.
Fudim	Method and apparatus for producing three-dimensional objects by photosolidification; radiating an uncured photopolymer	February 1987	U.S.
Arcella et al.	Casting shapes	March 1987	U.S.
Crump	Apparatus and method for creating three-dimensional objects	October 1989	U.S.
Helinski	Method and means for constructing three-dimensional articles by particle deposition	November 1989	U.S.
Marcus	Gas phase selective beam deposition: three-dimensional, computer-controlled	December 1989	U.S.
Sachs et al.	Three-dimensional printing	December 1989	U.S.
Levent et al.	Method and apparatus for fabricating three-dimensional articles by thermal spray deposition	December 1990	U.S.
Penn	System, method, and process for making three-dimensional objects	June 1992	U.S.

Early Parts

Although very intricate parts produced by rapid prototyping equipment are now common, the first parts out of these types of systems required a good deal of faith that improvements would occur. Shown in Fig. 3.12 are three early parts from different systems. The Housholder part was made from an embodiment that included a grid for separating mold material (concrete and water) from casting material (dry concrete). The Herbert part was created in August 1979. It is not known exactly when the Kodama and Housholder parts were created.

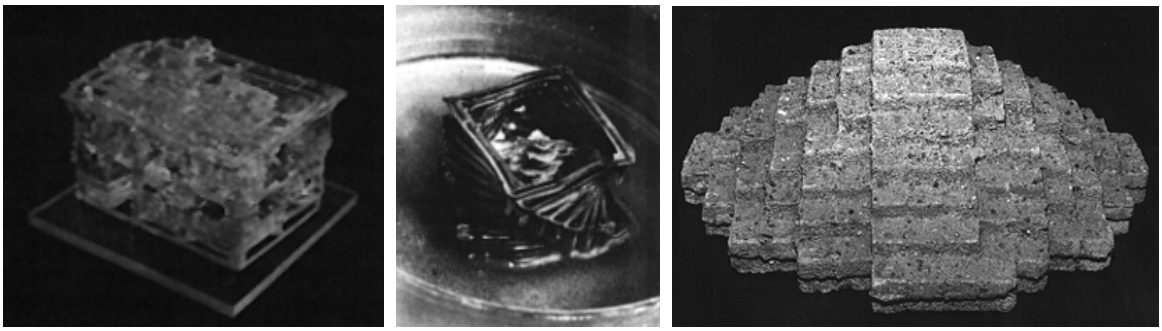


Fig. 3.12. Three early rapid prototyping parts; from left to right by Kodama, Herbert, and Housholder.

COMMERCIAL DEVELOPMENT

Early Development

In the earliest commercial development, Willème's photosculpture studio was commercially successful from 1861 to 1868 but eventually went out of business, probably due to the labor involved in hand sculpting with a pantographic (tracing) instrument. The next known commercial attempt was Swainson's formation of Formagraphic Engine Company in 1977. Formagraphic later formed an alliance with Battelle Laboratories and changed its name to Omtec Replication. It appears that this effort was abandoned before a commercial process was developed. Also in 1977, DiMatteo formed an company called Solid Photography that was spun out of Dynell Electronics Corporation when Dynell merged with United Technologies. As a result, an affiliated retail outlet called Sculpture by Solid Photography was opened in New York City (Fig. 3.13). In 1981, Solid Photography changed its name to Robotic Vision. Solid Photography and the company Solid Copier operated as subsidiaries of Robotic Vision until 1989 (Lightman 1996).

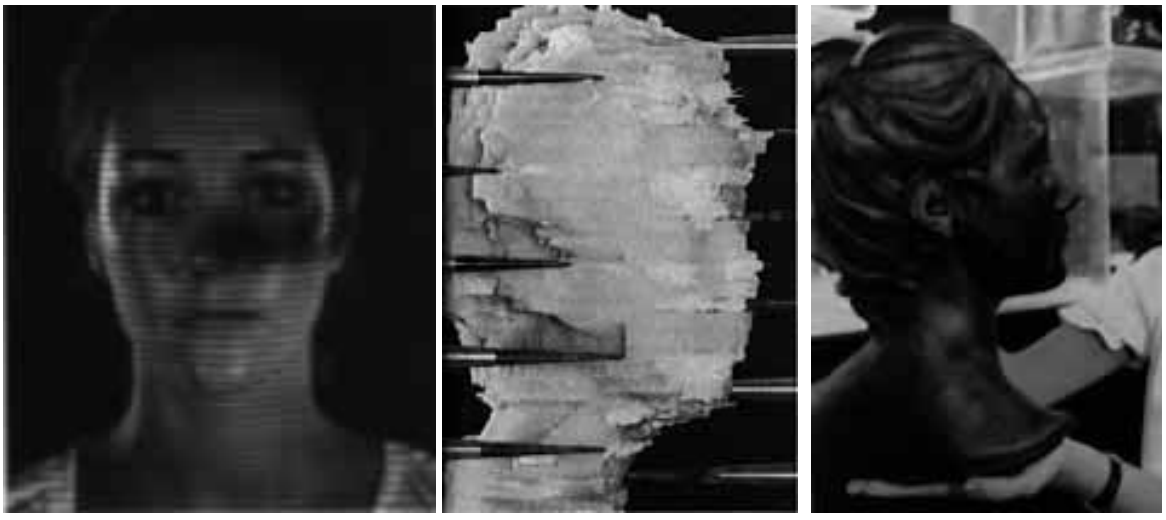


Fig. 3.13. Sculpture by Solid Photography process (Bogart 1979;
photos courtesy of Soho Image Works [no longer in business]).

U.S. Development

As Table 3.2 shows, the first commercial rapid prototyping machine was introduced in 1988 by 3D Systems when it shipped the SLA-1 to three customers.

Table 3.2
U.S. Commercial Development of RP Systems

Company	Process	Venture Start	Shipment	Notes
Aaroflex	Stereolithography	1995	n/a	License from DuPont
BPM	Ink jet	1989	1995	
DTM	Selective laser sintering	1987	1992	Operated a service bureau from 1990-93
DuPont Somos	Stereolithography	1987	n/a	Licensed to Teijin Seiki 1991, Aaroflex 1995
Helisys	Laminated object	1985	1991	Founded as Hydronetics
Light Sculpting	Photomasking	1986	n/a	Operates as a service bureau
Quadrax	Stereolithography	1990	1990	Technology acquired by 3D in 1992
Sanders Prototyping	Ink jet	1994	1994	Partially developed at E-Systems
Soligen	3D printing	1991	1993	Operates as a service bureau
Stratasys	Fused deposition	1988	1991	
3D Systems	Stereolithography	1986	1988	First commercial shipment of equipment

European and Japanese Development

Table 3.3 shows the chronology for commercial development of rapid prototyping processes in Europe and Japan. As can be seen by comparing these charts, the United States has led the way in commercialization of new rapid prototyping equipment. Also, it can be seen that in the United States there are many different types of technology, while in Japan, with the exception of Kira, all the Japanese vendors use laser photopolymer techniques. There is only one U.S. laser photopolymer company that is presently shipping equipment: 3D Systems.

Table 3.3
European and Japanese Commercial Development of RP Systems

Company	Process	Venture Started	Shipment	Notes
CMET	Stereolithography	1988, Japan	1990	
Cubital	Photomasking	1987, Israel	1991	
Denken	Stereolithography	1985, Japan	1993	
DMEC	Stereolithography	1990, Japan	1990	
EOS	Stereolithography, Selective Laser Sintering	1989, Germany	1990	
Fockele & Schwarze	Stereolithography	1991, Germany	1994	Service bureau since 1992
Kira	Laminated object	1992, Japan	1994	
Meiko	Stereolithography	1991, Japan	1994	
Mitsui	Stereolithography	1991, Japan	1991	
Sparx	Laminated object	Sweden	1994	Foam machine
Teijin Seiki	Stereolithography	1991, Japan	1992	License from DuPont
Ushio	Stereolithography	Japan	1994	

Fig. 3.14 shows an overall chronology of rapid mechanical prototyping. This chronology indicates some but not all of the major time events in the field.

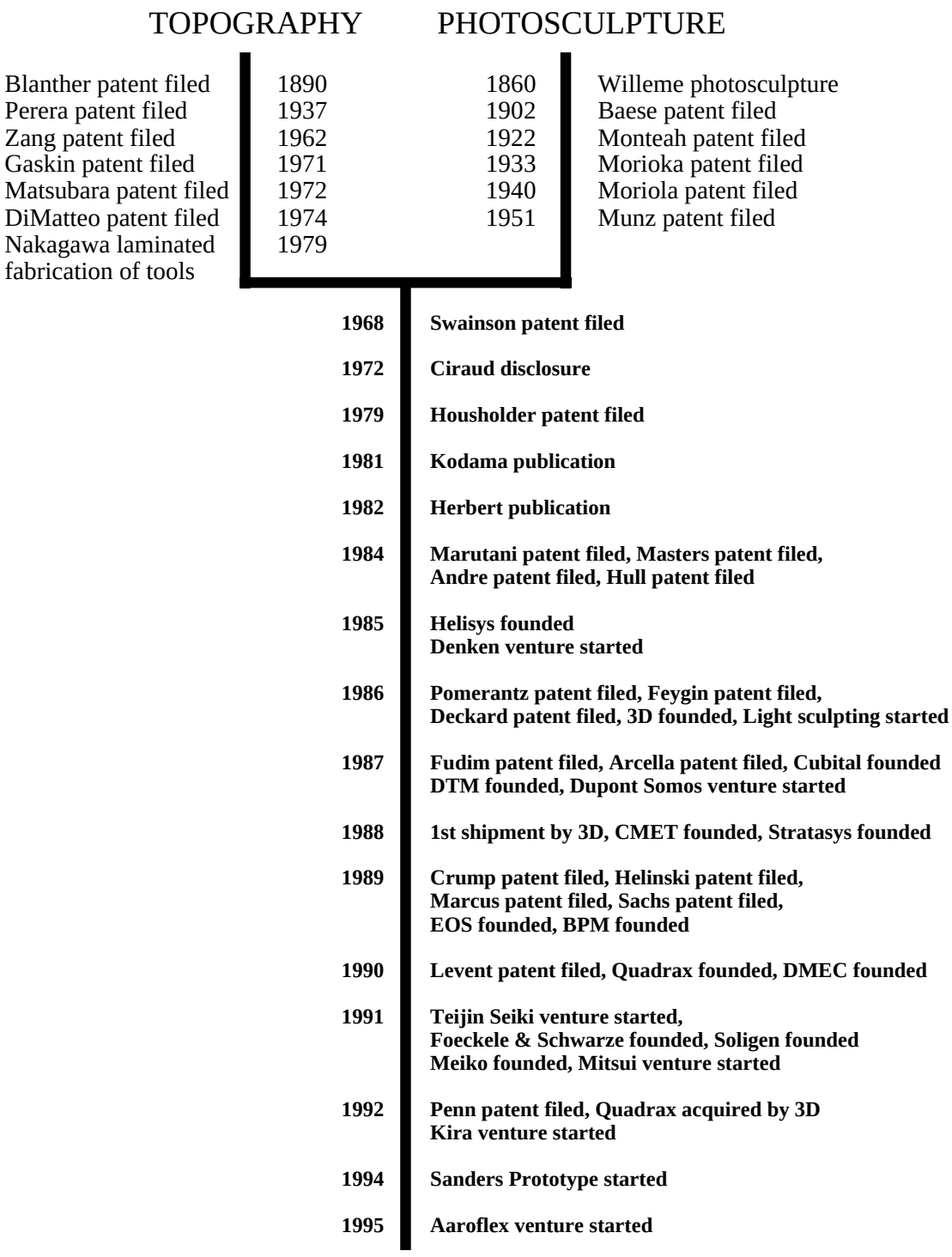


Fig. 3.14. Rapid prototyping chronology.

REFERENCES

Baese, C. 1904. U.S. Patent 774,549.

Blanther, J. E. 1892. U.S. Patent 473,901.

Bogart, M. 1979. In art the ends don't always justify means. *Smithsonian* 104-110.

Ciraud, P. A. 1972. FRG Disclosure Publication 2263777.

DiMatteo, P. L. 1976. U.S. Patent 3,932,923.

Gaskin, T. A. 1973. U.S. Patent 3,751,827.

Herbert, A. J. 1982. Solid object generation. *J. Appl. Photo. Eng.* 8(4)(August): 185-88.

Kunieda, M. and T. Nakagawa. 1984. Development of laminated drawing dies by laser cutting. *Bull. of JSPE* 353-54.

Kodama, H. 1981. Automatic method for fabricating a three-dimensional plastic model with photo-hardening polymer. *Rev. Sci. Instrum.* 1770-73.

Lightman, A. 1996. Personal communication.

Matsubara, K. 1974. Japanese Kokai Patent Application, Sho 51[1976]-10813.

Monteah, F. H. 1924. U.S. Patent 1,516,199.

Morioka, I. 1935. U.S. Patent 2,015,457.

_____. 1944. U.S. Patent 2,350,796.

Nakagawa, T., et al. 1979. Blanking tool by stacked bainite steel plates. *Press Technique* 93-101.

Nakagawa, T., M. Kunieda, and S. Liu. 1985. Laser cut sheet laminated forming dies by diffusion bonding. In *Proc. 25th Int'l. MTDR Conf.*, 505-510.

Perera, B. V. 1940. U.S. Patent 2,189,592.

Swainson, W. K. 1977. U.S. Patent 4,041,476.

Schwerzel, R. E., et al. 1984. Three-dimensional photochemical machining with lasers. In *Appl. of Lasers to Ind. Chem.*, SPIE, 90-97.

Zang, E. E. 1940. U.S. Patent 3,137,080.

CHAPTER 4

NEEDS, GOALS, AND OBJECTIVES

Robert L. Brown

The general needs, goals, and objectives for rapid prototyping are essentially the same in Europe and Japan, although the emphases may be different. Within a country, differences in needs also occur between and within industries. In Japan the tendency is to emphasize accuracy as the predominant consideration, while in Europe there is a movement to develop techniques to produce metal components and tooling. Both regions are interested in building rapid prototype (RP) plastic injection molds to produce a few hundred prototype parts in a commodity-type plastic. In the following discussion, the order in which needs and objectives are addressed does not necessarily represent the order of priority in any one country or industry; indeed, priorities vary between and within industries and companies.

RAPID PROTOTYPING

In general, the implementation of rapid prototyping by layer-building techniques has developed slower in Europe and Japan than in the United States. This may be a result of both Europe and Japan enjoying a greater infrastructure of skilled tool makers and model makers than does the United States. Also, U.S. industry tends to embrace new computer-related technologies more quickly.

Europe

Compared to the United States, Germany has been slower to adopt rapid prototyping in place of conventional machining techniques because many companies have not seen the need for it. There are still many small tool and machine shops in Germany that can produce a quality product at a reasonable price in a short time. Germany's machine shops are very competitive, with small tool shop owners willing to work nights and weekends to meet delivery dates.

Japan

Twenty years ago in Japan it was not uncommon to discuss with a company a new product or product design only to be presented the next day with a prototype of the proposed product incorporating features from the previous day's discussions. With skilled model makers and a culture that values dedication, Japanese companies took well-deserved pride in such feats. These capabilities still exist in Japan, albeit with an aging skilled workforce that is not being replaced by younger skilled practitioners at the rate older workers are leaving the industry. This is evident in both the jewelry and foundry pattern-making businesses, where RP

equipment is being introduced for production purposes to fill the shortfall in skilled workers. Other than in these cases and in specific companies discussed in this report, there has not been as great a perceived need for RP techniques in Japan as in the United States.

Still, both European and Japanese companies are using rapid prototyping, which suggests there is a need not being fulfilled by the conventional machine shops. Whether the driver is lower price, faster delivery, or curiosity to evaluate a new technology is not clear. Certainly, the driver is not dimensional accuracy, material properties, or surface finish, as all of these qualities can still be better achieved by conventional machining techniques.

3D CAD SOLID MODELING

The key element in the efficient use of RP is application of 3D solid modeling software, starting at the point of design inception. Without this tool, transfer of design data can be time-consuming and laborious. There is less use of 3D solid modeling software in Europe than in the United States, and even less in Japan. This may be partially due to the recession Japan has endured during the past several years, which has limited capital spending in most companies.

Representatives of a Japanese service bureau speculated to the JTEC/WTEC team that 10% of large Japanese companies own 3D CAD solid modeling software, and 1% know how to use it. Others estimate that 3% of Japanese designers can use 3D solid modelers. Officials at another service bureau told panelists that 80% of their customers supply CAD files, but the files are only in 2D. Generally, prototypes can be made in Japan quicker, cheaper, and more accurately by conventional machine shop practices if designs are supplied as 2D files. Only when parts are small, have complicated surfaces, and are designed in 3D CAD solid modeling can prototypes be built more quickly and less expensively by RP techniques.

There is an interest in Japan in finding easier methods for designers to build RP models without having to use full 3D solid modeling software. For example, Sony wants to develop 2D CAD software that would be easier to use than solid modeling packages, but that could produce 3D RP models with specialized control software. The goal of Professor Fukuda of the Tokyo Metropolitan Institute of Technology is to develop a CAD system that allows the designer to use a “more intuitive approach” to modify and manipulate the model (Sites, 1996, 117-118). At the time of the JTEC/WTEC panel’s visits in Japan, large companies like Mitsubishi Electric Engineering Company were ordering 3D CAD solid modeling software from the United States, but until recently only relied on 2D drawing tools (*Electronic News* 1996, 32).

RAPID PROTOTYPING EQUIPMENT

For RP equipment, the primary needs, regardless of country, are lower equipment cost, lower maintenance costs, greater accuracy, better surface finish, and higher speed; however, relative importance of these factors does vary.

Equipment Costs

While some new U.S. equipment makers are focusing on lowering costs, such as for desktop RP units, the drive to develop low-cost equipment does not appear to be a major consideration in Europe. The European equipment maker EOS is positioning itself as a high-cost premier producer of equipment, and Cubital units have been consistently at the high end of the cost range.

In Japan, RP equipment equivalent to that available in the United States is considerably more expensive. In comparison, machine tool centers in the same size class as an RP machine are less expensive than stereolithography units. Yet, inexpensive, albeit lower-accuracy, units are available for the jewelry industry

from such companies as Meiko, which produces a photo resin-based unit with a price tag of ~$140,000, including software. For some Japanese equipment makers, lowering equipment costs is becoming an objective. D–MEC representatives mentioned price as a customer concern; consequently, this Japanese company plans to develop lower-cost machines in the future.

Maintenance Costs

For RP equipment using lasers, the lasers themselves can be the highest maintenance cost item. Fockele and Schwarze (Sites, 1996, 14-17) has been evaluating diode-pumped Nd lasers with frequency triplers to replace the argon ion lasers that are more expensive to maintain. EOS has been offering these diode-pumped Nd lasers commercially on its STEREOS MAX laser stereolithography units for some time and has sold several such systems to customers. Diode-pumped Nd lasers are expected to have longer life, be less expensive to replace, and consume less power.

In Japan, maintenance contracts appear to be comparable in cost to those in the United States, but resins are much more expensive.

Accuracy and Surface Finish

Improvement of accuracy and surface finish are often primary considerations for users of RP equipment. As more companies attempt to build prototype plastic injection mold cavities by RP, the need for greater accuracy and surface finish in the RP master copy will increase, since some degradation of part dimensions occurs in the injection molding process.

Daimler Benz representatives indicated that with stereolithography they can routinely achieve 100 micron accuracy in the x-y direction and 250 microns in the z direction. They would like 70 micron accuracy in all three directions. (Such tolerances are already achievable in the United States.) JTEC/WTEC panelists talked with observers of the European RP industry who indicated that it is not always clear what user needs are for accuracy in a prototype part; in some cases, current dimensional tolerances are sufficient.

Stereolithography is the most popular RP method in use in Japan. When panelists asked why selective laser sintering units are not as popular in Japan as in the United States, the explanation offered was that stereolithography provides the greatest accuracy. Generally, Japanese companies would like to see higher accuracy capabilities, where tolerances of ±0.03 mm can be routinely achieved (Sites, 1996, CMET and Olympus site reports, 42-46, 95-98). Representatives of Shonan Design Company, a service bureau, mentioned to panelists that their customers indicate they will increase orders for RP parts as accuracy and surface finish improve.

Speed

Speed appears to be an important consideration in Europe, as shown by the fact that BMW underwrote the first EOS stereolithography unit based on a speed-performance standard. Automaker Daimler Benz would also like to see speed increases in the recoating operation, and other companies indicated that speed is an important consideration.

Compared to the United States, less consideration appears to be placed on speed in Japan. As an example, less emphasis is placed by some Japanese RP equipment manufacturers on providing software to automatically design structural supports for the parts being built, leaving customers to laboriously design supports by manual techniques (Sites, 1996, CMET/Asahi Denka report, 42-46). However, a Sony representative did mention speed as one attribute of Sony's next-generation RP machines (Sites, 1996, D-MEC report, 47-53).

MATERIALS

There is a clear need to improve the mechanical properties of the stereolithography resins and plastics currently being used. Cubital is searching for an epoxy-type material that will match the properties of 3D Systems' epoxy resin and for a wax-like material that can be used for investment casting of metal parts. The Institute for Polymer Testing and Polymer Science at the University of Stuttgart has helped EOS develop a polystyrene for selective laser sintering. As laser-sintered, this material has relatively low strength and is generally used for investment casting patterns or visualization models. Although it can be infiltrated to produce high-strength rigid parts, polyamide (nylon) is generally used for parts requiring higher strength and/or toughness. Users such as Daimler Benz desire models that have the mechanical properties of ABS; that is, with ductility to test snap fit, flexible hinges, and other functional properties of a design.

Full-density resins, which may be produced by stereolithography, selective laser sintering, or infiltration, will not replicate the mechanical properties of a part produced by plastic injection molding, due to rheological considerations in the molded plastic parts that can align the anisotropic polymers to produce different mechanical properties in different directions within the part. In a similar manner, sintered metal parts do not replicate the mechanical properties of fully dense wrought or cast products. Properties in plastic parts that approach what might be expected from production parts can only be achieved using rapid tooling to produce injection molded parts. Equipment and resin makers, research institutes, and others, see the need to develop rapid tooling methods and materials to (1) produce parts that approach the mechanical properties of production parts, and (2) be able to make a few hundred parts for functional testing.

Stereolithography Resins — Properties and Cost

A prime consideration in both Europe and Japan is the development of resins that have improved mechanical properties, better long-term dimensional stability, higher temperature resistance, and lower cost. Better mechanical properties give designers greater latitude in using RP models to test functional characteristics (Sites, 1996, Olympus report, 95-98). Several companies expressed the desire to achieve properties equivalent to those of ABS.

Greater dimensional stability over time (i.e., 30 days) is also needed. When Japan's Ministry of International Trade and Industry (MITI) made funds available to develop better resins, one attribute that it specified as an objective was time-dependent dimensional stability (Sites, 1996, D-MEC report, 47-53). Resin makers are also developing epoxy-based UV curable resins to reduce warping.

Higher thermal stability is desirable in rapid prototyping resins when used for (a) producing plastic injection molds that are used for making a few hundred prototype parts in a common plastic, and (b) making functional models that have to withstand elevated temperatures, such as for functional testing of the intake manifold of an internal combustion engine.

Stereolithography resins are also expensive. Service bureaus such as Schneider in Germany would like to see price breakthroughs in resins to make them more competitive (Sites, 1996, 7). A single large vat of stereolithography resin can cost $100,000 in Japan. For companies that make large parts, such as intake manifolds for engines, this is a significant issue (Sites, 1996, Hino Motors report, 58-9).

Metals

In Europe there is considerable activity in devising processes that will directly yield metal components. In processes using powder metals in selective laser sintering-type methods, the resulting RP products are porous. They can be furnace-sintered to consolidate the objects, but this results in extensive shrinkage and loss of dimensional accuracy. The alternative is to infiltrate with a lower-melting-point alloy or a high-temperature epoxy resin that does not require furnace sintering. Infiltrated products represent a compromise: they do not have good high-temperature properties and often have too low a hardness and wear resistance compared to fully dense steel objects; however, they are often adequate for pilot tooling for making a few thousand

injection-molded parts. The Fraunhofer Institute for Production Technology (IPT) is developing a process to directly make fully dense metal parts by a laser fusion process called Laser-Generated RP, which incorporates a milling cutter to trim the walls and surfaces of each layer to improve accuracy and surface finish. The process was first shown publicly December 1995 at Euromold 95 in Frankfurt, Germany. Similar techniques are being pursued in the United States, but without integrated machining.

There are two forms of metal tooling: pilot tooling and production tooling. The long-term objective of European research institutes and equipment makers is to develop RP hardware and processes to produce production tooling. However, accuracy is a major issue. In producing pilot metal tooling, achievement of a high degree of accuracy and of mechanical properties approaching those of wrought metal are serious considerations. Achieving both of these properties at the same time is not currently possible.

It is clear that in Europe there is a need for metal parts produced by rapid prototyping for tooling and structural components. At the RP service bureau Schneider Prototyping near Frankfurt, 15-20% of orders are for metal parts and tooling. Panelists were told that German companies often send their rapid prototyping models or CAD files to the United States to have them cast into metal parts because price and quality are better than in Germany. German casting foundries have been slow to learn casting methods that use rapid prototyping masters for investment casting patterns.

The JTEC/WTEC panel found no company in Japan developing RP processes to directly build metal components, but did find considerable interest in making metal components by investment casting, metal spray, and so forth.

Ceramics and Paper

Compared to the United States, there does not appear to be much interest in Europe and Japan in building ceramic parts by RP. At the time of the panel's visit, several companies and institutes in Europe were working on developing ceramic processes, but the emphasis appeared to be on polymer resins and metal products.

In Japan, Kira Corporation, which builds a small laminated paper (or object) manufacturing (LOM) machine, would like to see its process capable of greater accuracy. It is now limited to ±0.1 mm/25 mm in the horizontal plane (x-y direction) and ±0.3 mm/25 mm in the vertical build direction (z direction). Swelling of the completed part in the z direction due to humidity can also be a problem, which Kira researchers hope to correct with an improved paper (Sites, 1996, 75-83).

PLASTIC INJECTION MOLDED PROTOTYPES

Tooling to make molds that will produce 200-500 plastic parts in 3-4 weeks is a goal of Schneider Prototyping. The Fraunhofer Institute for Chemical Technology (ICT) is experimenting with making epoxy resin plastic injection molds using stereolithography. EOS offers a selective laser sintering unit specifically designed for making metal molds using a proprietary bronze-based metal powder. At the time of the panel's visit, the Fraunhofer IPT was experimentally using this machine to produce parts using stainless steel, aluminum, and coated ceramics powders, although it was not specifically designed to support these materials.

The Japanese service bureau Shonan Design has developed a technique for making injection mold cavities that can produce 200 injection molded parts in 2-3 weeks using Teijin Seiki's stereolithography units and glass-filled resin. However, accuracy is no better than ± 0.3 mm over the length of small parts (~12 mm) for up to 200 parts. Japanese equipment and resin makers that compete with Teijin Seiki also are working to develop resins that can be used to make prototype molds. Laser sintering was generally not being used in Japan at the time of the panel's site visits, nor did panelists see evidence that Japanese firms were attempting to develop such techniques. Since then, over two dozen selective laser sintering machines have been installed in the Asian Pacific Rim. At least two of these machines are in Japan.

EDUCATION

Several of the 46 Fraunhofer institutes in Germany are developing educational courses in various aspects of rapid prototyping for small- and medium-sized companies. Judging from the number of RP conferences and commercial RP courses in Europe, there is a strong interest in such programs. Warwick, Nottingham, and Buckingham universities in England have developed or are developing consortiums with industry that are designed to educate industrial personnel as well as to pursue specific developmental goals.

While Japanese companies traditionally have not worked closely with universities or research institutes, this is changing. Japanese industry has apparently begun approaching universities for help in educating the engineering workforce in order to help companies keep up with rapidly changing technologies. To cite a specific example, Terry T. Wohlers of Wohlers Associates, in reviewing a draft of this report, indicated that in June 1996, Prof. Nakagawa of Tokyo University described to him "a one-year, $1.5 million Japanese government project with Toyota Electronic and Telecom Institute in Nagoya. The focus of this work is to produce production tooling by laser-cutting and laminating steel sheets. Toyota has produced and used as many as 100 dies using Nakagawa's sheet lamination approach for prototype tooling… [Also,] Nakagawa is working with Professor Takeuchi of Tokyo Electronic and Telecom Institute on high-speed 5-axis machining." The JTEC/WTEC panel interviewed several Japanese who are doing outstanding academic work in support of RP (Sites 1996, 117-124) and learned of several new industry-government programs that focus on new manufacturing technologies. However, the panel learned of no specific RP programs in Japan that jointly involve industry, university, and government.

GOVERNMENT SUPPORT

It is difficult to construct a simple picture of how funds flow in Europe from government agencies to industry and academia to further the development of RP. This is because of the high number of overlapping and interwoven local government, federal government, and European Community agencies' programs that provide support. For example, there is support for RP-related programs from the Commission of the European Communities through BRITE/EuRAM, RACE, ESPRIT, COMPLAN, and EARP. Some programs like EARP (European Action on Rapid Prototyping), which is under BRITE/EuRAM (Basic Research of Industrial Technologies for Europe/European Research on Advanced Materials), have very limited funds for distribution. "BRITE funds basic research while EuRAM focuses on European research on advanced materials. In the 1993-94 period, BRITE/EuRAM supported most of the European RP projects. ESPRIT is involved more on the computing side. The EUREKA program is supported jointly by the EC and national governments, whereas BRITE and ESPRIT are funded exclusively by the EC."[1] In addition, there are federal and state government programs. When seven Fraunhofer institutes initiated their alliance to coordinate their RP programs (the JTEC/WTEC team visited four of these. See Sites 1996, 18-33), the German government gave the alliance DM 5 million (~$3.5 million) over two years to fund start up. In other RP efforts, approximately 50% of the operating funds to support the Bayerisches Laserzentrum (Bavarian Laser Center) come from local state government, and the innovative service bureau Fockele and Schwarze received startup funding through a Westphalia government program that further backed its loans through a local bank (Sites, 1996, 1-3, 14-17).

In Japan, MITI's position appears to be that RP is not a serious commercial process because of the poor surface finish, material properties, and accuracy of its products. (A number of Japanese companies, on the other hand, do consider RP to be a serious commercial process.) The Ministry is not yet committed to investing substantial resources to support RP. Government officials estimated at the time of the JTEC/WTEC visit that it would be at least eight years before RP becomes a serious commercial technology and before Japanese RP equipment companies will compete in sales on a world scale. Currently, RP represents less than 1% of the NC (numerical control) machine tool market and therefore enjoys only minor support from MITI compared to its past support of Japan's machine tool industry, which has 48% of the world machine tool

[1] This explanation was contributed by Terry T. Wohlers.

market. However, MITI does fund a ¥800 million 4-year RP program that is administered through the government laboratory, Center for Plastic Materials, which distributes ¥200 million per year. The funds are available to industry to support research and development activities in four areas: (1) resins, (2) hardware, (3) software, and (4) applications. Japan Synthetic Rubber Company, which owns the stereolithography equipment manufacturer D-MEC, is the only company obtaining funds from MITI for materials development under this program. INCS, Inc., has a ¥30 million project to develop RP tooling and another ¥800,000 to develop medical models.

Japan's Ministry of Education, Science, and Culture is moving from a position of promoting basic science in universities to stressing the importance of manufacturing. In another departure from general past practices, MITI intends to fund manufacturing projects directly at universities. As these changes only appear to be recent, panelists had little or no discussion in Japan about RP training programs for industry. In general, prefectural governments sponsor local programs for industry and education, which may be another source of funds to support development activities.

In summary, it is apparent that European industry, universities, and research institutes are identifying and addressing practical needs in RP and are moving forward with determination to establish well-thought-out development programs that will produce a solid foundation of basic knowledge on which to build further advancements in RP. In Japan, the links between industry, academia, and research institutes do not seem to be quite as strong as in Europe. It is clear to this panel that the Japanese have a long-term plan to be major, if not dominant, competitors on a global scale in RP. They have demonstrated in other fields that they can produce a superior product by identifying practical needs and quietly addressing all details to produce a complete solution.

REFERENCES

Electronic News. 1996. (January 8): 32.

Sites. 1996. This reference designates the companion volume to this JTEC/WTEC report: Prinz, F. B., ed. *JTEC/WTEC panel report on rapid prototyping in Europe and Japan.* Vol. II. *Site reports.* Baltimore, MD: Loyola College. NTIS Report #PB96-199583.1.

CHAPTER 5

MATERIALS — OVERVIEW, PLASTICS, AND RESINS

Paul S. Fussell

STATE OF RP MATERIALS DEVELOPMENT

The aim of rapid prototyping is to rapidly produce a product. At the moment, this product is made, for the most part, of inferior material that permits the user to show notion, or perhaps generate a few other parts suitable for limited testing. This condition has been true since the initial systems were commercialized, while the promise of true engineering products is only slowly being realized through machine and material improvements. Heralding this achievement is a gradual progression up the maps of material properties. Although Fig. 5.1 reduces the complexity of material choice and performance to just the two parameters modulus and strength, it shows a simplified schematic of this progression.

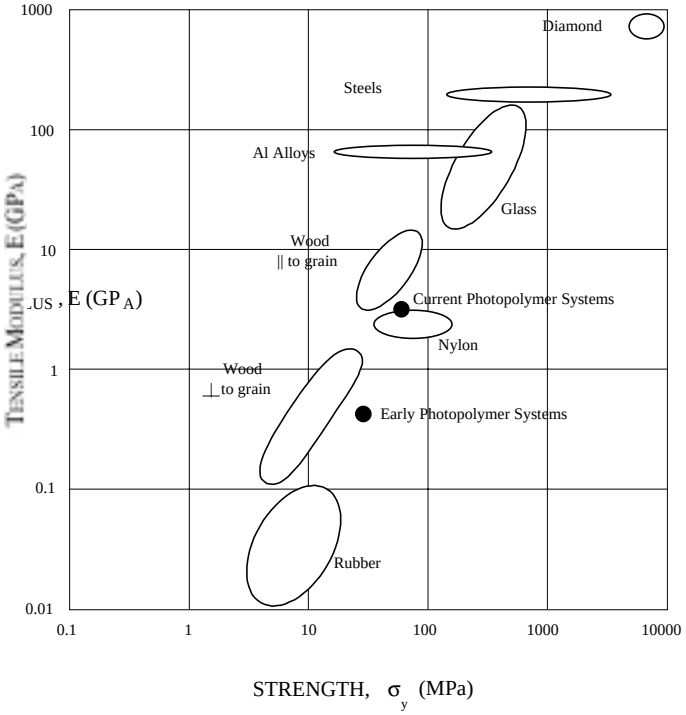


Fig. 5.1. Modulus-strength materials property chart, after Ashby (1989).

The progression, however, is not sufficiently advanced to speak to the real need of the rapid product developers: this community needs rapid prototype materials that behave, with high fidelity, like engineering materials, and specifically engineering polymers. Rapid prototyping is having a useful effect on product visualization and other limited fields, but the lack of rapid prototyped engineering materials is a significant barrier, perhaps the single most significant barrier, to dramatic growth of this technology and its profound impact on the product development endeavor. For the panel's observations during this review, there is little visible work that will produce this new material.

Given non-engineering material, the viability of any rapid prototype effort hinges upon the integrated success of material, machine, and the information used to drive the device. This strong interdependence manifests itself in every nuance of the equipment's design, performance, and eventual optimization. There are numerous examples of this linkage in extant rapid prototyping technology. One is 3D Systems' ability to successfully commercialize QuickCast™. This was made possible by the use in the SLA-250 of the epoxy resin SR 5170, with its properties of accuracy, dimensional stability, and weakening in the presence of high-temperature steam, in conjunction with successful design of the internal lattice structure of the solid object (Jacobs 1995). It is fair to say that the epoxy material has substantially added to the shareholder's value in 3D Systems, Inc., as well as changed the resin market in the United States and Europe.

Improvement and optimization of rapid prototyping approaches is equally dependent upon both material and machine design. For DTM to successfully introduce the nylon material, it had to apply a new level of sophistication in thermal control of the powder column. Similarly, 3D Systems had to make significant control parameter alterations to deal with the difference between the kinetics of epoxy cure and the earlier acrylate systems.

In commercial rapid prototyping, there is also the delicate art of finding a balance between material properties, material cost, equipment cost, ease of use, and overall system performance and throughput. Each vendor of equipment chooses a different price point for its technology and vigorously proceeds to develop its relevance to the marketplace. This is certainly as true in Europe and Japan as it is in North America.

It is therefore germane to study the state of materials development in rapid prototyping, as well as the interweaving of material design and machine design. This chapter explores the state of materials development — polymers, metals, and ceramics — in the European and Japanese rapid prototyping environments, with limited comparison to North America.

PLASTICS

The use of plastics in the rapid prototyping industry is, broadly speaking, broken into two categories: (1) reactive polymer systems such as the photopolymers used in stereolithography equipment, and (2) nonreactive polymers used, for example, in the sinter-based systems. Research and development in these areas have been equally effective in moving the materials closer to the property performances of engineering plastics.

In terms of market share, the North American rapid prototyping materials market is dominated by Ciba Geigy's epoxy line of resins (SR 5170, 5180, and 5190), and by DTM's powder systems, including nylon, wax, and polycarbonate.

Reactive Polymer Systems

The polymers of this phylum are thermoset in character: that is, the polymer chains grow and cross-link during curing. The cure system is initiated by energy input to the resin, and in rapid prototyping systems, most generally by light (usually ultraviolet). The basics of these reactions are amply covered in Johnson (1994) and Pang (1995) .

To understand the Japanese market, readers should be aware of the terminology in use. In rapid prototyping, resin systems are categorized in Japan as acrylate chemistry and epoxy chemistry types. The *acrylate system* uses a free radical method of polymerization, whereas the *epoxy system* uses a cationic method of polymerization. There are also thermally initiated polymerizations, principally in the epoxy chemistries.

The cationic systems (commercialized in North America by Ciba Geigy, DuPont, and Allied Signal), and the epoxy systems in particular, show high accuracy and low distortion performance, and have markedly better properties than the earlier resins. The initial commercialization of Ciba Geigy's resin 5170 was achieved in July 1993 (Pang 1995). Fig. 5.2 shows the relative performance of representatives of the current set of North American photopolymers.

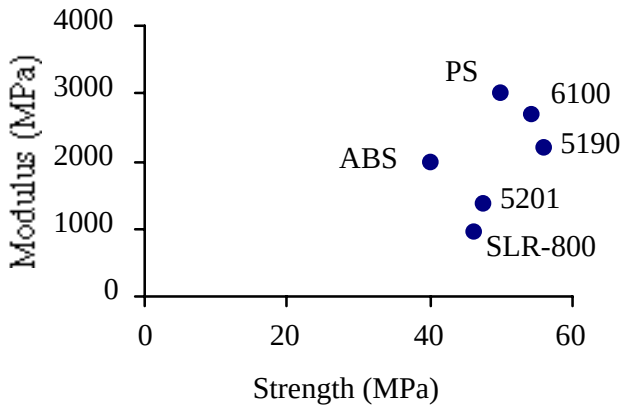


Fig. 5.2. Modulus vs. strength plot of extant photopolymers in North American market (see also Table 5.1).

Table 5.1 shows some of the particulars of these same resins. The polystyrene row gives representative values for the material of comparison used in the North American market. ABS is the representative material in the Japanese market.

In this gross summary of properties, some of the tensile strength and modulus properties of photopolymers are now approaching those of some commodity materials. This is born out by inspection of other properties as well.

Table 5.1
Modulus and Strength Values, Extant Photopolymers in N. American Market

Resin	Tensile Strength	Tensile Modulus
Medium strength polystyrene (PS)	50 MPa	3000 MPa
ABS-molded, medium impact	40 MPa	2000 MPa
Ciba Geigy SR 5190	56.0 MPa	2200 MPa
DSM SLR-800	46.1 MPa	961 MPa
DuPont SOMOS 6100	54.4 MPa	2690 MPa
Allied Signal Exactomer 5201	47.6 MPa	1379 MPa

RESINS

Table 5.2 summarizes the rapid prototype manufacturer and material vendor relationship.

Table 5.2
Resin Suppliers to RP Equipment Manufacturers

Equipment Manufacturer	Resin Supplier
Cubital	Unknown
Fockele & Schwarze	Allied Signal/DuPont
EOS	DuPont
Laser 3D	Self-formulated
Teijin Seiki	Teijin Seiki/DuPont
CMET	Asahi Denka
D-MEC	Japan Synthetic Rubber
Denken	Self-formulated (680 nm λ)
Meiko	Shikoku Kenka Industry

Resin Approaches

The JTEC/WTEC panel found the European and Japanese work in filled, or loaded, resins to be interesting. This is a partially undeveloped market in North America, although DuPont's SOMOS 2100 and 5100 series resins are filled. The new work is being pushed in Japan, and the Institute for Polymer Testing and Polymer Science at the University of Stuttgart has also done some investigative work.

The filled systems generally have a much higher viscosity: they produce a stiff artifact after curing; they can be wear-resistant depending upon the matrix and the reinforcement; and they can have the effect of increasing accuracy by simply replacing the variable polymer with an inert component. At the same time, they reduce cost, again, by simply substituting a cheap material for the more costly polymer.

The panel investigated 3 filled resin systems now being developed by three manufacturers:

- Teijin Seiki tooling application
- Japan Synthetic Rubber tooling application
- Laser 3D (France) cost control, accuracy

Table 5.3 summarizes some of the properties of these manufacturers' resin systems. The uses of these resins are detailed in Chapter 11 on tooling applications of rapid prototyping.

Table 5.3
Filled Resin Characteristics

Manufacturer	Resin	Viscosity	Filler	Particle Size, wgt %
Teijin Seiki	TSR 752	49,000	5 components	~30–50 µm
JSR	SCR 600	3400	glass	15 µm, 70%
Laser 3D	MR 100	~10,000	glass*	10–20 µm, 60%

* Laser 3D suggests that it is using SiC, ceramic, and wax as well, although the panel did not observe these being used.

The European market primarily uses resins produced by North America-based manufacturers. The Japanese market, however, primarily uses suppliers based in Japan. These suppliers include Asahi Denka, Japan Synthetic Rubber, and Teijin Seiki.

Asahi Denka Resins

Asahi Denka has an exclusive arrangement with CMET of the Mitsubishi group. Its resins are all epoxy-based and have been in the market since about 1990. Several of the U.S. and European manufacturers indicated they were aware of these systems, but the North American market didn't see an epoxy system until 1993. The properties of the Asahi Denka resins are interesting, with high strength and high modulus values, as Fig. 5.3 and Table 5.4 show. It is apparent, though, that Asahi Denka and CMET have chosen to have a relatively brittle material. In comparison, North American manufacturers produce resins that have somewhat reduced modulus and strength properties but are less brittle.

The HS 673 is apparently the most popular argon ion laser material. This material does show dimensional change with humidity, growing from 0.1% to 0.3% initially, and 0.5-0.6% with long exposure.

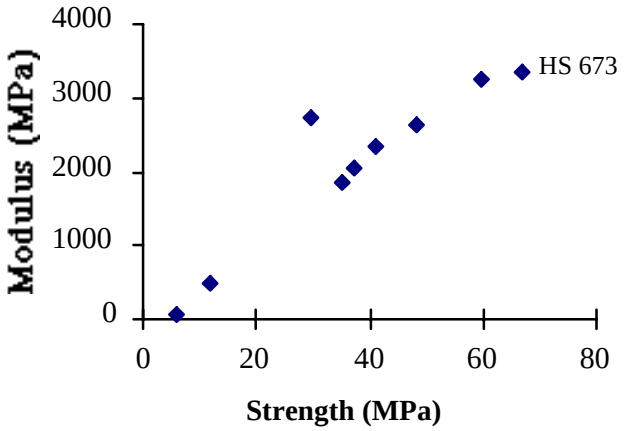


Fig. 5.3. Asahi Denka resins: modulus vs. strength properties (see also Table 5.4).

Table 5.4
Asahi Denka Materials: Modulus vs. Strength

Resin	Laser	Strength	Modulus	Elongation	Impact
HS 671	Ar	29 MPa	2746 MPa	1.3%	1.3 ft–lb/in
HS 672	Ar	48 MPa	2648 MPa	2.8%	1.8 ft–lb/in
HS 673	Ar	67 MPa	3334 MPa	3.1%	2.2 ft–lb/in
HSX–A–4	Ar, experimental	35 MPa	1863 MPa	3.7%	3.1 ft–lb/in
HS 660	HeCd	60 MPa	3236 MPa	2.5%	2.2 ft–lb/in
HS 661	HeCd	41 MPa	2354 MPa	2.9%	2.0 ft–lb/in
HS 662	HeCd	37 MPa	2059 MPa	4.7%	3.7 ft–lb/in
HS 663	HeCd	12 MPa	481 MPa	16.0%	13.8 ft–lb/in
HS 666	HeCd	6 MPa	69 MPa	10.0%	14.5 ft–lb/in

Figures 5.4 and 5.5 show the relationships of elongation and impact resistance vs. strength. Note that CMET publishes unnotched IZOD data; thus, it is difficult to compare to engineering data for conventional materials. The HS 673 shows low elongation, low impact resistance, and high strength.

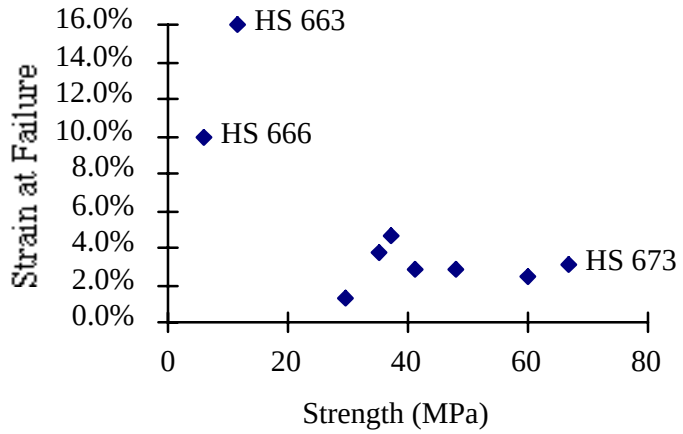


Fig. 5.4. Asahi Denka resins: strain at failure vs. strength (see also Table 5.4).

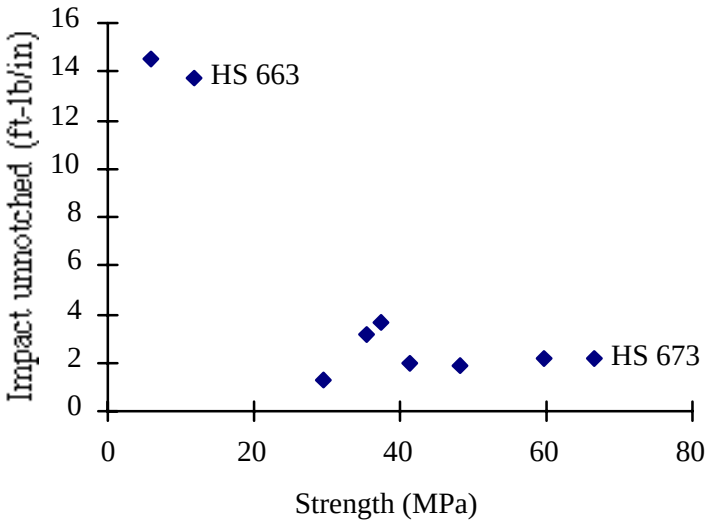


Fig. 5.5. Asahi Denka resins: impact vs. strength properties (see also Table 5.4).

Japan Synthetic Rubber Resins

Sony has commercialized the Japan Synthetic Rubber (JSR) resins in the DMEC devices. These are all acrylate urethane resins. As shown in Table 5.5 and graphically in Fig. 5.6, these are less strong and less stiff than the epoxy systems. The JSR material SCR 310 is intended to provide low warpage service, and SCR 600 is an experimental resin filled with glass. (The SCR 600 work is funded by MITI.)

Figures 5.7 and 5.8 show the elongation and impact resistance tradeoffs that JSR made in formulating the materials.

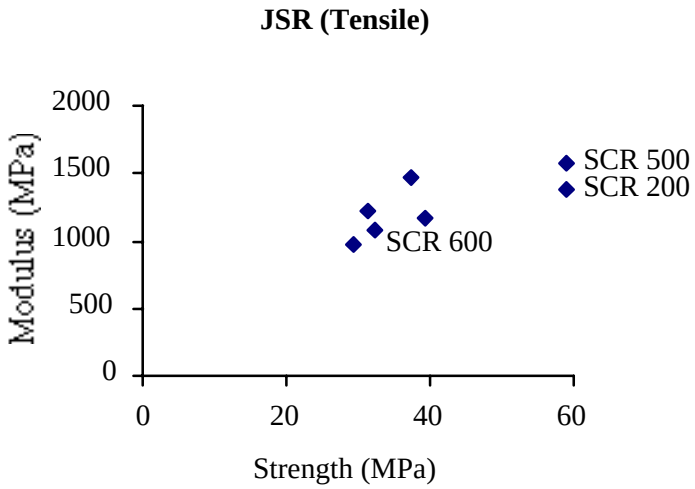


Fig. 5.6. Japan Synthetic Rubber resins: modulus vs. strength properties (see also Table 5.5).

Table 5.5
Japan Synthetic Rubber Material Properties

Resin	Tensile Strength	Tensile Mod	Strain at Failure	Flex Strength	Flex Mod	Impact notched	Impact unnotched	T_g	Heat Defl't
SCR 100	31 MPa	1.2 GPa	5%	62 MPa	1.4 GPa	0.37 ft-lb/in	3.1 ft-lb/in	95°C	54°C
SCR 200	59 MPa	1.4 GPa	15%			0.55 ft-lb/in	2.75 ft-lb/in	93°C	50°C
SCR 500	59 MPa	1.6 GPa	10%			0.37 ft-lb/in	3.3 ft-lb/in	140°C	75°C
SCR 310	39 MPa	1.2 GPa	30%			2.75 ft-lb/in	8.6 ft-lb/in	110°C	43°C
SCR 600	32 MPa	1.1 GPa	5.6%	382 MPa	1.2 GPa	2.2 ft-lb./in	7.3 ft-lb./in	93°C	44°C

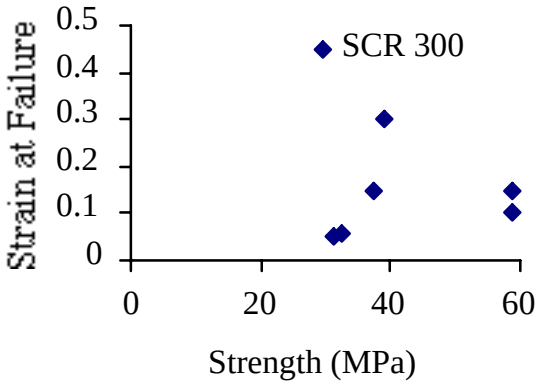


Fig. 5.7. JSR resins: strength vs. elongation (see also Table 5.5).

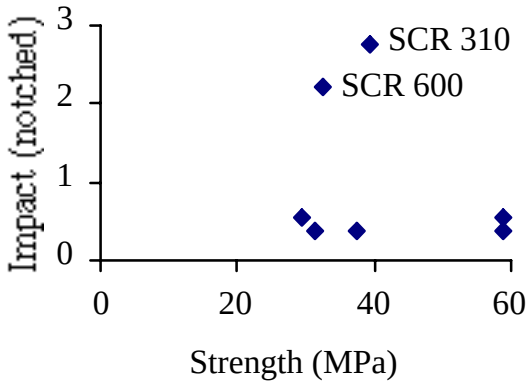


Fig. 5.8. JSR resins: strength vs. impact resistance. (see also Table 5.5).

Teijin Seiki Resins

Teijin Seiki is committed to the tooling market in Japan. The company has determined that prototype tooling, if of sufficient accuracy, will be appealing to a very large market. Its material development began only two years ago; formerly it purchased DuPont SOMOS materials from North America. Its resin TSR 752 is a filled resin showing very high stiffness and reasonable strength. Its sole application is tooling. Fig. 5.9 shows the modulus vs. strength information, and Table 5.6 summarizes the material data.

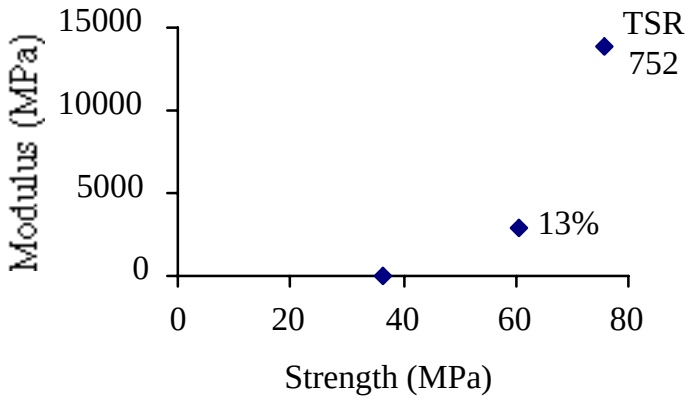


Fig. 5.9. Teijin Seiki resins: modulus vs. strength properties (see also Table 5.6).

Table 5.6
Teijin Seiki Material Data

Resin	Tensile Strength	Tensile Modulus	Strain at Failure	Flex Strength	Flex Modulus
TSR 752	76 MPa	14,000 MPa	1%	97 MPa	14,000 MPa
TSR 800	61 MPa	2900 MPa	13%	100 MPa	2800 MPa

Overview

Fig. 5.10 shows an overview of the major Japanese resins.

Additional Approaches

In addition to the major materials and vendors discussed above, there are other approaches to material issues. Cubital has developed, originally with DSM, material for its Solid Ground Curing system. These are basically acrylate systems, although Cubital has felt the marketing pressure from the Ciba Geigy epoxy system and is attempting to develop such a resin as well.

Table 5.7 shows the elongation and heat deflection temperature of Cubital resins, and Fig. 5.11 shows the modulus vs. strength mapping. The softness of these resins shows that parts from these materials will be competitive with the other acrylates, but not with the epoxies.

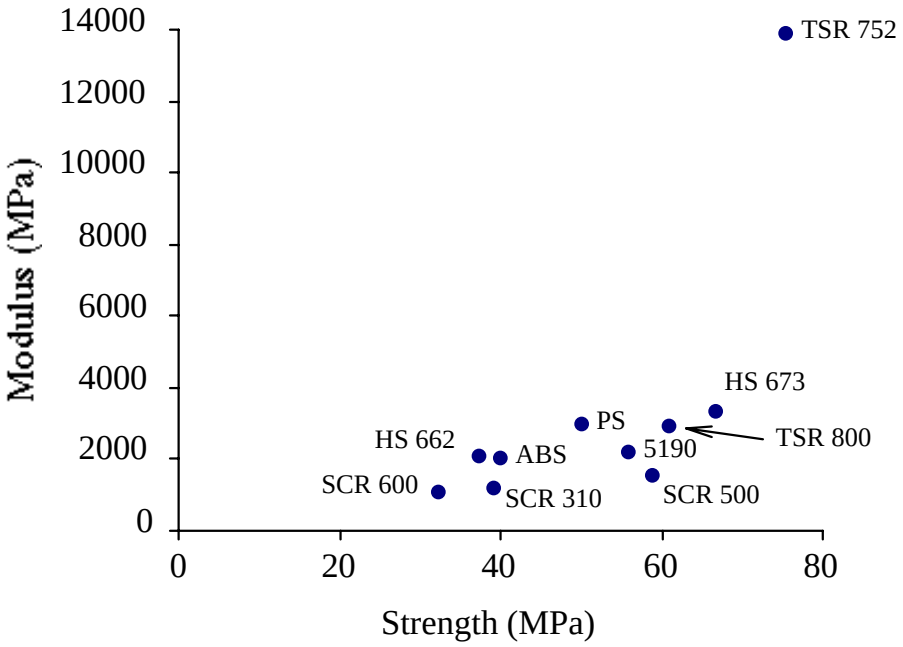


Fig. 5.10. Comparative overview of Japanese resin systems.

Table 5.7
Cubital Resins: Elongation, Heat Deflection Temperature

Resin Type	Elongation	Heat Deflection Temperature
G5601	10%	40°C
XA7510	20%	54°C
X611	10%	51°C
“Epoxy”	10%	80°C

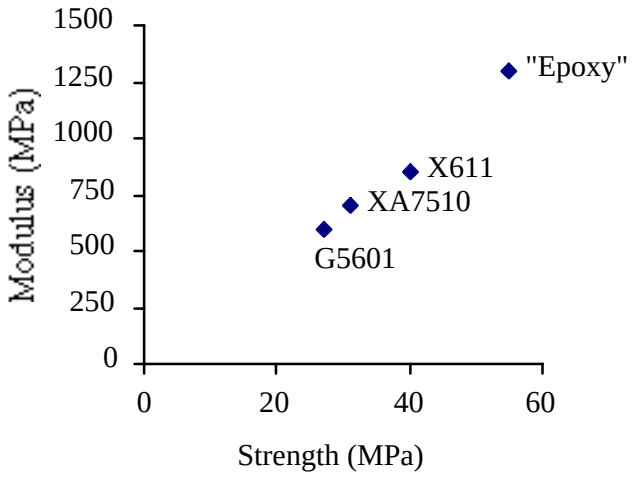


Fig. 5.11. Cubital resins: modulus vs. strength properties.

Denken has used a single acrylate sensitive to its visible light laser. Since it is now converting to a frequency doubled laser (at 473 nm λ), the company will be able to explore other resin systems.

Similarly, Meiko has a specialized resin for use with its HeCd laser. This resin gives adequate performance for the jewelry modeling niche market Meiko has developed.

THERMOPLASTIC SYSTEMS

Almost all development of thermoplastic systems is taking place in North America. EOS in Germany has a line of polymers for its EOSINT machines that includes polystyrene for investment casting, a nylon-like material, and a polymer-coated sand material. EOS uses the sand in its EOSINT-S device to make one-of-a-kind sand cores for precision sand casting. In the European market there has been considerable interest in this product, especially for those applications that require very complex sand cores.

OTHER SYSTEMS

Kira Corporation makes parts in paper in a process that uses knives to cut the outline of the layer rather than using a laser to burn the outline. Kira's work, however, is still grounded in conventional office papers. Its customers have recognized that better paper is needed, and Kira is apparently beginning to study the possibility of using rice paper.

ROLE OF JAPANESE MARKET DEMAND

The Japanese market is dominated by a concern for accuracy. This has led the companies competing there to focus on liquid-based systems and to optimize them for precise parts. One Japanese host mentioned to JTEC/WTEC panelists that of the 140 RP machines in Japan at the time of the panel's visit, fully 50% of them were not usable because they were too inaccurate. The accuracy requirements of several companies visited by the panel include these:

- ±0.1% typical, with less than ±0.1 mm variation across a 50 cm span
- ±0.1 mm in a bolt hole

Representatives of the companies that the panel visited observed that the technology they had access to did not deliver these accuracies — basically they were a factor of two away from achieving these.

The ±0.1 mm variation across a 50 cm span is nearly within reach using epoxy and the larger of the 3D Systems machines in the North American market.

One other discussion regarding the resin market was on the subject of why the resin companies in Japan do not enter the U.S. market. JSR representatives indicated JSR would consider selling anywhere, while representatives of CMET, the holder of the exclusive license to sell Asahi Denka's resin, indicated the company was only willing to sell resin in areas where its machines are sold. This specifically excludes the U.S. market.

OBSERVED RESEARCH DIRECTIONS

The JTEC/WTEC panel observed several directions for research. In Japan, CMET executives commented that the future of Japanese rapid prototyping was in rapid production of metal molds. This was consistent with observations made by Professor Nakagawa of Tokyo University and also Mr. Yamada of INCS.

One Japanese host commented that Hitachi, Toshiba, Matsushita, and NEC all would like to develop rapid prototype technology, but that if the market remains small for RP technology in Japan, then these players will not enter the arena. Teijin Seiki is developing a new resin system with Professor Endo at the Tokyo Institute of Technology. This will be a monomer-based system designed to deliver ±50 µm accuracy. Representatives of several Japanese companies alluded to new resins being developed by their companies. These included JSR, which was trying to formulate an epoxy system.

In Europe, the Catholic University of Leuven is developing with Zenica of Britain a resin system that changes color with additional irradiation. This is of particularly interest for medical models, to show, for example, a diseased area in the highlighted color.

GOVERNMENT AND STRATEGIC EFFORTS

MITI is providing very modest funds for resin development in Japan. JSR is currently the only recipient of the MITI funds. The MITI program targets the following values:

- Accuracy: ±0.05 mm RMS on a 10 cm user's part
  ±0.1 mm RMS on a 30 cm user's part
- Stability: ±0.05 mm movement in 1 day
  ±1 mm movement in 1 month

The Fraunhofer institutes are more oriented toward new applications and new metal materials than toward new resin systems.

TRENDS FOR FUTURE WORK

In the resin systems, there is healthy global competition to refine the current resins and, apparently, to look for the next resin to introduce a step change in material properties. There is every expectation that this will continue.

The lack of investigation of filled resins outside of Japan is of some concern. However, if the direct metal or high-dimensional-quality cast metal schemes work, then the need for a filled resin tool will be greatly reduced.

Researchers' eyes should be trained on the goal of dramatically moving RP materials up the property map (Fig. 5.1). In resins, this is being done primarily in the competitive marketplace.

REFERENCES

Ashby, M. F. 1989. *On materials and shape.* No. CUED/C–Mats./TR 170. Cambridge University.

Jacobs, P. F. 1995. The development of QuickCast. In *Stereolithography and other RP&M technologies,* ed. P. F. Jacobs, 183–207. Dearborn, MI: Society of Manufacturing Engineers.

Johnson, J. J. 1994. Molecular bonding fabrication. In *Principles of computer automated fabrication,* 44-56. Irvine, CA: Palatino Press.

Pang, T. H. 1995. Advances in stereolithography photopolymer systems. In *Stereolithography and other RP&M technologies,* ed. P. F. Jacobs, 27-80. Dearborn, MI: Society of Manufacturing Engineers.

CHAPTER 6

MATERIALS — METALS

Joseph J. Beaman

INTRODUCTION

Rapid prototyping can be used to create metal parts by fabricating patterns for casting applications, as Chapter 10 describes. This chapter describes processes that create metal parts and tools in a more straightforward fashion. A major proposed application for these processes is metal tooling, especially injection mold tooling.

Various nomenclatures are used to describe rapid prototyping processes that create metal objects. At the University of Texas, the three major metal processing methods are called *transfer methods, indirect methods,* and *direct methods.*[1] In simple terms, transfer methods use patterns — either castings or spray metal patterns (this JTEC/WTEC panel did not address the subject of spray metal). Indirect methods (which could also be called low-density matrix methods) involve making relatively low-density metal objects and then infiltrating or post-sintering these objects to high density. Direct methods (which could also be called high-density methods) create high-density metal structures without a secondary processing step. There are already commercial applications of the indirect methods; the direct methods are all still in the research stage.

The United States has strong research and commercial activities for creation of metal tooling by rapid prototyping techniques. Europe also has very strong research and development programs in both direct and indirect metals processes. In addition, Europe is creating a broad-based technological infrastructure for this work. The coordinated programs of Germany's Fraunhofer Institutes are particularly effective. The panel is aware of no indirect or direct rapid prototyping metals research or development work in Japan, except for that by Nakagawa, which will be discussed in the Japan section of this chapter.

INDIRECT METHODS

3D Printing

Three-dimensional printing, as shown in Fig. 6.1, is a rapid prototyping process being developed at MIT. In 3D Printing (3DP), an ink jet printing head can be used to selectively inject a binder into a metal powder bed. The selectively bound part, when later removed from the bed, is a relatively low-density (about 50% dense) "green" part. The green part is then subsequently fired and infiltrated to make a dense metal part. Fig. 6.2

[1] This terminology is by no means universal. For example, the term "direct tooling" is used to describe indirect methods of creating metal tooling to differentiate them from "indirect" transfer methods.

shows an early example of a mold made in the process. Even at this stage of development, there are some interesting features in this mold. This mold has internal cooling channels built right into it — something very difficult to achieve with standard machining processes. Fig. 6.3 shows a more recent mold, illustrating the advances being made. This tool is made of stainless steel-bronze, and the injection-molded plastic parts are glass-filled nylon.

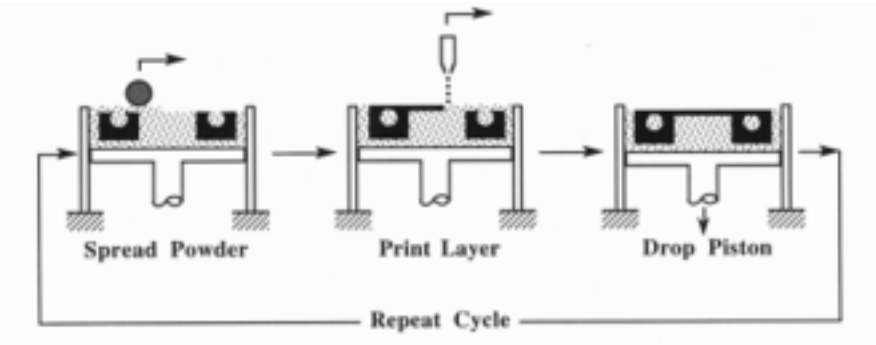


Fig. 6.1. Schematic of 3D Printing process.

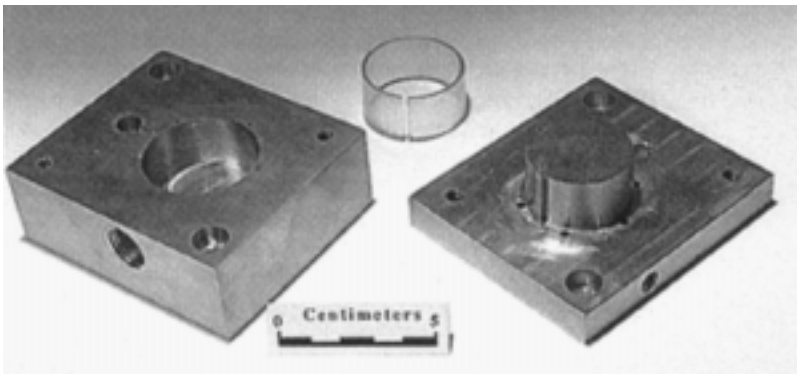


Fig. 6.2. 3DP mold exhibiting internal cooling channels.

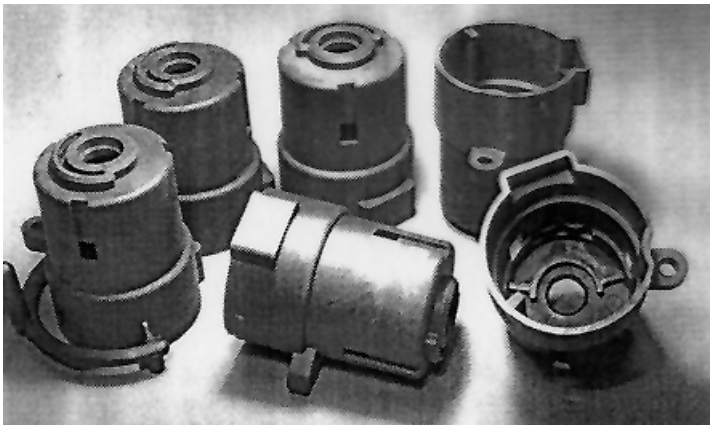


Fig. 6.3. 3DP mold and resulting injection-molded connectors.

Selective Laser Sintering — Indirect

Selective laser sintering (SLS) is a rapid prototyping process first developed at the University of Texas. The indirect process for fabricating metal parts and molds is commercially available from DTM Corporation. In this process, metal powders are coated with a thermoplastic binder. These coated powders are then selectively fused together with a laser in the SLS process. This bonds the metal powders together to form mold components represented by a CAD file, thus producing a green part. The green part is then post-processed in a furnace, where the binder is burned out, and the metal powders are bonded together through traditional sintering mechanics. This part is now referred to as a "brown" part; it exhibits geometry but is also porous in nature. The brown part is then infiltrated with a second metal to form a fully dense mold. Fig. 6.4 is a schematic of the entire process. Fig. 6.5 shows a commercial core and cavity set that was created with this process. The properties of this mold are similar to those of 7075 aluminum.

DIRECT METHODS

Methods of rapid prototyping that can be used directly to fabricate metal objects include selective laser sintering, shape deposition, laser deposition, and droplet deposition. Droplet deposition is under development at the University of Southern California and also at a company called Incre. These techniques use electronically controlled jets to selectively deposit molten metal. Since no apparent development of this process is being conducted in either Europe or Japan, no further discussion will occur in this report.

Fig. 6.4. DTM's RapidTool™ process for rapid mold making.

Fig. 6.5 Core and cavity sets produced by RapidTool™.

Selective Laser Sintering — Direct

By using higher temperatures and higher-power lasers (>50 W), selective laser sintering can be used to create high-density metal layers. Fig. 6.6 shows a relatively high-density layer (about 125 µm) of Inconel 625 superalloy. This layer was formed in the SLS process with a Nd:YAG laser at 60 W of laser power. Research is underway at the University of Texas using this process to fabricate high-density metal parts with a variety of powdered metals and alloys.

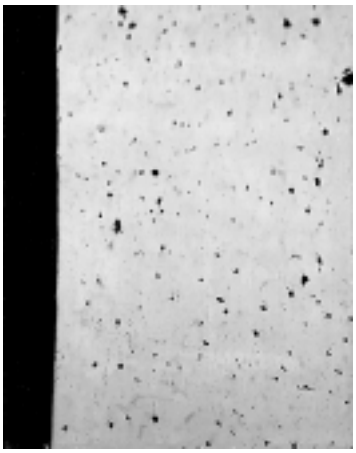


Fig. 6.6. Inconel 625 layer formed in an SLS process.

Shape Deposition

Shape deposition (also described in Chapter 2) is under development at Carnegie Mellon and Stanford universities. Shape deposition manufacturing (SDM) first deposits layers as near-net shapes and then machines them to accurate dimensions before additional material is added. Fig. 6.7 shows a part produced by this process. The part does not have detailed features yet, but it is composed of two different materials: a stainless steel core and an outer shell with copper inlays (not visible in the figure). Multiple materials offer the promise of building integrated components in one operation.

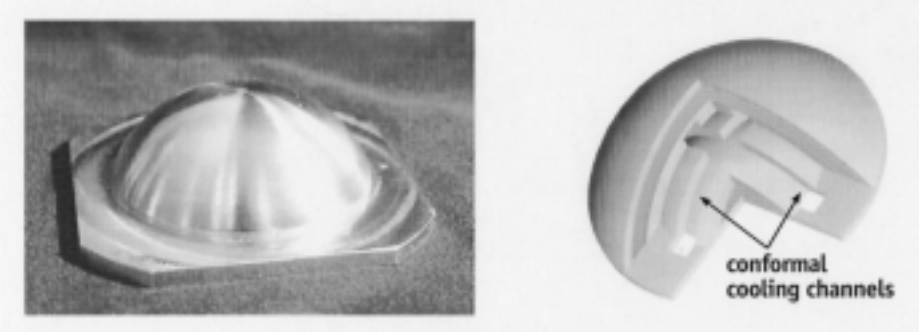


Fig. 6.7. Stainless steel-copper structure built with SDM.

Laser Deposition

Fig. 6.8 is a schematic of a laser deposition process being developed at Sandia National Labs; a similar process is under development at Los Alamos National Labs. This process consists of a powder delivery system and a laser beam; the powder delivery is designed to intersect with the laser delivery simultaneously, to build up objects in a layer-like fashion. In essence, the process consists of 3D laser welding. Fig. 6.9 shows objects created by Sandia's laser deposition process. They are made of almost 100%-dense 316 stainless steel.

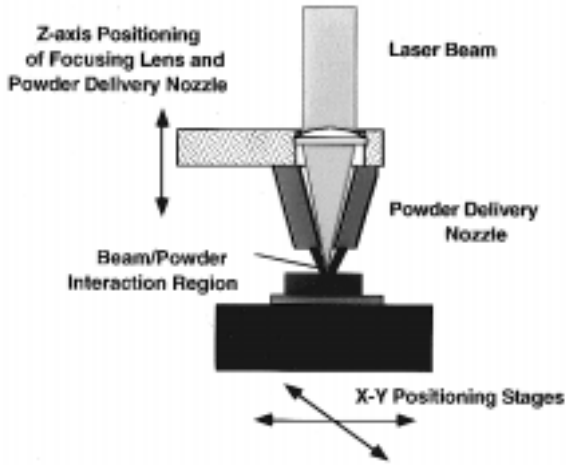


Fig. 6.8. Schematic of a laser deposition process.

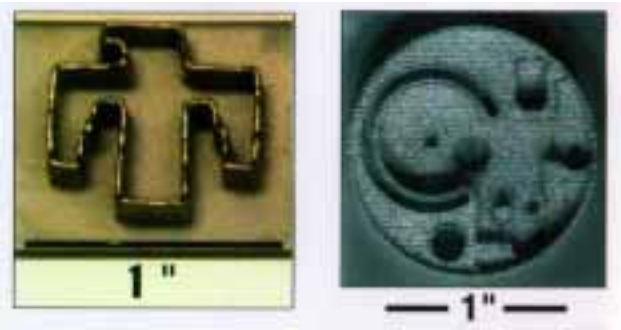


Fig. 6.9. Stainless steel objects created by laser deposition process at Sandia.

Lamination

As described in Chapter 2, lamination of laser-cut sheets can also be used as a rapid prototyping process. If the sheets are metal, then metal parts and molds can be fabricated by stacking and bonding these sheets. Professor Nakagawa at the University of Tokyo Institute of Industrial Science has been the primary researcher of this technique.

EUROPEAN METALS R&D

European Projects

There are a growing number of funding sources in the European Community (EC) for rapid prototyping with metals. Although there are certainly other projects in metals rapid prototyping in Europe, the main projects that were specifically discussed by the panel's hosts are shown in Table 6.1. The panel has only limited information about these projects.

Table 6.1
European R&D Projects for Rapid Prototyping with Metals

AGENCY	PROJECT
German Government	Fraunhofer Strategic Alliance for Rapid Prototyping (aka "Rapid Prototyping Network")
EC (BRITE EuRAM)	Development of rapid prototyping technologies based on laser sintering
Baden-Württemburg State	Generative Manufacturing (RP manufacturing of tooling)

Fraunhofer Rapid Prototyping Network

There are currently 46 Fraunhofer Institutes in Germany, 3 Fraunhofer Resource Centers in the United States (in Ann Arbor and Boston), and several others worldwide. Of these, seven have allied themselves into the Fraunhofer Rapid Prototyping Network: the Institute for Chemical Technology (ICT) in Berghausen; the Institute for Applied Materials Research (IFAM) in Bremen; the Institute for Graphic Data (IGD) in Darmstadt; the Institute for Laser Technology (ILT) in Aachen; the Institute for Manufacturing Engineering and Automation (IPA) in Stuttgart; the Institute for Production and Construction Technology (IPK) in Berlin, and the Institute for Production Technology (IPT) in Aachen. The goal of this network is the development, advancement, and dissemination of innovative rapid prototyping technologies. The main emphasis is placed on metallic prototypes. Within this framework, two processes are being emphasized: (1) laser sintering of metal powder, and (2) laser deposition techniques.

The Fraunhofer rapid prototyping alliance received DM 5 million from the Fraunhofer Society as start-up funds. It started operation in September 1994 and is expected to return 150% of the funding in industrial contracts in 4-5 years (see also Sites 1996, 18-19).

EC BRITE EuRAM: Development of Rapid Prototyping Technologies Based on Laser Sintering

This completed EC BRITE EuRAM program investigated existing rapid prototyping technologies in combination with new process chains. Project partners included the Institute for Polymer Testing and Polymer Science (IKP) at the University of Stuttgart, UPC Barcelona, DPS Turin, EOS, and Microtechnia. Particular tasks in this project included process modeling and model testing, laser sintering optimization, advanced workstation design, and rapid tool fabrication.

Baden-Württemburg State Project in Generative Manufacturing

This project also involves the investigation of existing rapid prototyping processes in combination with new process chains, focused on manufacture of functional prototypes and tools in small batches. Particular concern is given to the environmental impact of rapid prototyping systems and processes. Partners in this project are the University of Stuttgart-IKP, Ascam, Emil Bucher, Invenio, Andreas Stihl, Hermann Bubeck, EOS, and KL-Technik. Tasks for this project include manufacture of injection molding tools, testing and optimization, property evaluation, and environmental and economic impact studies.

European Metals Research Organizations

This brief review is of the metals research organizations that the JTEC/WTEC panel visited, confined for the most part to Germany and Japan. No attempt is made to review sites not visited. There are certainly other notable European metals research efforts.

BLZ (Bavarian Laser Center)

The BLZ began operation in January 1994. The mandate of this center is the transfer of university research in the area of laser-based manufacturing to industry, especially to small- and medium-sized companies. Particular metals rapid prototyping research foci at the BLZ are selective laser sintering and lamination of laser cut sheets. The BLZ is also working on lamination, in which individual cross-sections are laser-cut from metal sheets and then stacked and bolted together to form a tool insert.

The BLZ's partner for laser sintering is EOS. Together, they are working on machine and process improvements for an EOS metal sintering machine (see next section) using an Electrolux bronze-nickel alloy. The BLZ concentrates on the development of a dual-beam laser that has a central beam for sintering and a surrounding field for preheating. Parts are subsequently infiltrated with solder to achieve higher strengths.

EOS

EOS is a 70-person German company with headquarters and R&D facilities in Planegg. Zeiss recently purchased a majority stock position in the company. EOS manufactures and sells three models of stereolithography machines and three categories of sintering machines. One of these sintering machines, EOSINT M, is for metal powder. The particular metal powder that EOS was using at the time of the JTEC/WTEC visit was a modified version of the bronze-nickel alloy developed and patented by Electrolux for the manufacture of dimensionally precise pieces using pressureless sintering techniques. Fig. 6.10 is a picture of an EOS sintering machine, and Fig. 6.11 shows laser-sintered mold inserts made of the Electrolux material and of a hard metal material developed at IFAM.

The Fraunhofer Institute for Chemical Technology (FhG ICT)

The ICT was created in 1959 to provide research and expertise to the German military for chemical-based explosives. With the end of the Cold War, its mission was expanded to include industrial chemical problems. Although ICT's materials expertise is primarily in polymers, not metals, it has an active research program in the indirect method of fabricating metal parts and tools with polymer-coated metal powders in the laser sintering process. For its metals research, ICT has an experimental laser sintering device equipped with a 100 W Nd:YAG laser. For environmental temperature control, the laser's focus point is inside a commercial oven. The immediate program is to produce very thin coatings on metal powders to be used as feedstock for laser sintering machines. Another thrust is to provide a controlled texture to the coating. ICT researchers hope to use texturing to minimize the amount of coating needed for green parts and thus reduce shrinkage upon secondary firing of the green part. They hope to reduce the amount of polymer binder to 1 wgt %. One area of interest is carbon coating of iron particles; after oven-sintering, they hope to show a steel structure with full density. The metal alloys of long-term interest are those of the current tooling industry: H13 and P20 steels.

Fig. 6.10. EOS laser sintering machine.

Fig. 6.11. Laser-sintered mold inserts: (left) Electrolux material; (right) hard metal (developed at IFAM).

The Fraunhofer Institute for Applied Materials Research (FhG IFAM)

IFAM researchers started developing plans for rapid prototyping research in 1991. IFAM has a mission to serve industry worldwide. In rapid prototyping, this mission extends to developing application-oriented solutions to industry problems, systems integration for industry, and education and training of industry personnel. IFAM is working with EOS to develop metal sintering. In this regard, it has an EOSINT 160 machine. This unit has a 100 W CO_2 laser and a 160 mm^3 build volume. This unit is not equipped with powder preheat or with an inert gas environment.

The IFAM-EOS research concentrates on Electrolux bronze-nickel powder. IFAM performs the infiltration research required for the parts from this system. Parts are infiltrated with $PbAg_2Sn_2$ solder alloy with a melting point of 315°C. Parts made from this process have been used as injection molds. Development is underway to find lead-free infiltrants. Fig. 6.11 shows a sample of parts from this process.

In addition to its work with EOS, IFAM is developing a multiphase jet solidification (MJS) process in cooperation with FhG IPA (Greulich 1995). The MJS process is similar to Stratasys' fused deposition modeling (FDM) process. In the MJS process, a polymer (wax) is loaded with 50%-volume metal powder and then extruded through a nozzle to build a green metal part. The green part is then processed in a similar fashion to other indirect metal methods. Fig. 6.12 shows a green and a sintered part made in this process.

Fig. 6.12. 376L parts produced in the MJS process at IFAM (counter-clockwise from upper right): granulate, green part, and sintered part.

Fraunhofer Institute for Manufacturing Engineering and Automation (FhG IPA)

In 1988 IPA started a rapid product development group within its Department of Information Processing. IPA has several government- and industry-sponsored projects, including the Rapid Prototyping Network. This network account for 20% of IPA's rapid prototyping efforts. Its primary research in metals pertains to its joint work with IFAM on the MJS system. IPA is responsible for upgrading the software and IFAM is upgrading the hardware, with the goal of commercializing the next-generation system.

Institute of Production Technology (FhG IPT)

The IPT was established in 1980 near the Technical Institute of Aachen and next to the Machine Tool Institute. It started its research in rapid prototyping in 1992. Since that time IPT has developed two experimental direct metal rapid prototyping systems. One system is a laser sintering workstation equipped with a 300 W Nd:YAG laser, normally operated in the 200 W range. The beam is moved with a scanner mirror system from above the work chamber to provide a work area 100 mm in diameter that can be shrouded with a protective gas. The system is not designed to hold an atmosphere in the work chamber. This unit is used for direct laser sintering of uncoated metal powders, including bronze-nickel (Electrolux material), aluminum, copper, and 316L stainless steel. With this unit IPT has achieved up to 90% theoretical density. Fig. 6.13 shows a sample part from this system.

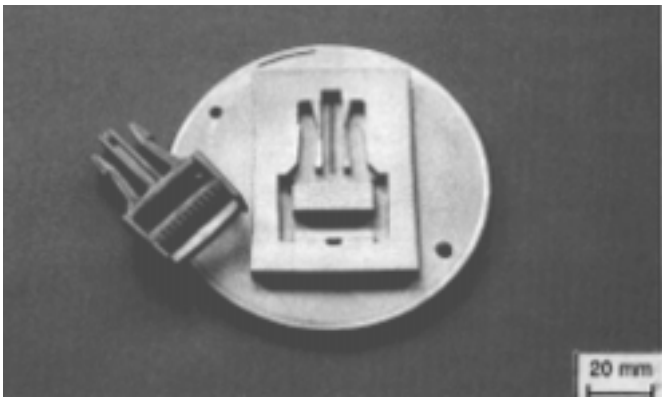


Fig. 6.13. A direct metal part fabricated in a laser sintering system at IPT.

IPT's second experimental system, called laser-generated RP, is designed to melt metal powder as it drops from a coaxial laser/powder distribution cone. This process is a variant of laser deposition. Other concentric cones within the process head deliver shroud gas and fluids for cooling. Either a 900 W CO_2 laser or a 1,000 W Nd:YAG laser can be used in this experimental setup. Within the work chamber is a 2½D milling cutter to finish layers and improve tolerances and finish. IPT plans to commercially develop this system with a German company over the next few years. Fig. 6.14 shows an early version of this system.

Fig. 6.14. Laser-generated RP process.

The Fraunhofer Institute for Laser Technology (ILT), which is located across the street from IPT, is also involved as support to these projects.

Catholic University of Leuven

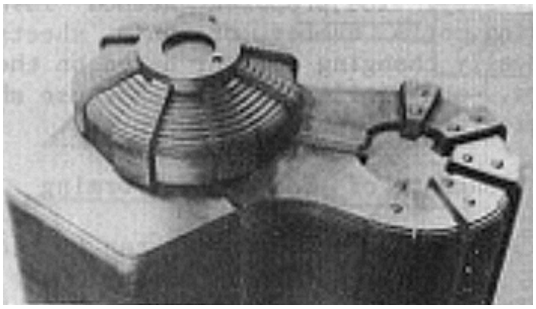
Rapid prototyping is a thrust area of the Division of Production Engineering, Machine Design, and Automation (PMA), which is the largest of four divisions of the Department of Mechanical Engineering at the Catholic University of Leuven. In one project, the PMA has built a prototype laser sintering machine for direct fabrication of metal components. The unit uses a 500 W Nd:YAG laser with a fiberoptic head, an xy stage for beam delivery, and a 5 mbar vacuum environment working chamber. The machine had only been operational for a short time when the panel visited, with current research focused on steel/copper powders.

University of Stuttgart Institute for Polymer Testing and Polymer Science (IKP)

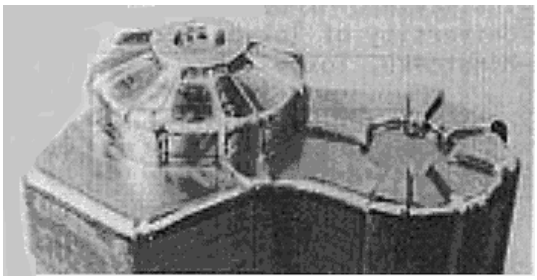
The IKP was founded in 1963 and started its rapid prototyping activities in 1991 with high-power laser metal melting. The IKP metal process is based on laser deposition and is similar to the IPT system. IKP researchers used it for building material from single lines, but they found the process too restrictive and expensive. The IKP has a joint project with the ILT that uses a nozzle and a high-power laser in a lathe system. Materials studied include nickel- and cobalt-based alloys.

JAPANESE METALS R&D

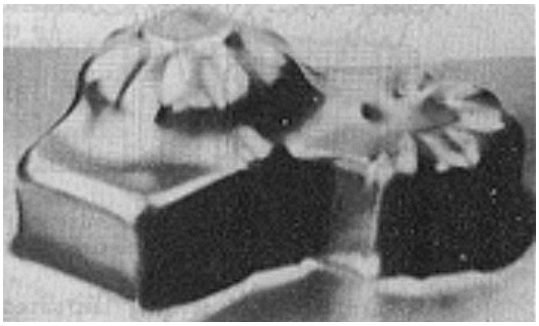
As compared to the European metals research activities, the Japanese research activity is almost nonexistent. The one exception is the significant research of Professor Takeo Nakagawa of Tokyo University's Institute of Industrial Science. Professor Nakagawa's work started very early (Nakagawa 1979). By laser-cutting sheet metal and laminating the laser-cut sheets, Nakagawa is able to create three-dimensional metal structures. This concept was first experimentally applied for the production of blanking tools and later utilized for forming tools. Recently, it has been applied to rapid prototyping of metal parts. Fig. 6.15 shows a laminated punch tool and the resultant part. In 1985, Nakagawa et al. created injection molds with exotic cooling channels.



Photograph of the laminated punch before smoothing.



Finished punch.



Sample part.

Fig. 6.15. Laminated tool created by Nakagawa.

CONCLUSION

As can be seen in the foregoing discussion, Europe has very strong research programs in metals rapid prototyping, especially in Germany. Along with these programs, Europeans are creating an impressive research infrastructure in the field.

In contrast, except for Professor Nakagawa's leading-edge work, the JTEC/WTEC panel is aware of no Japanese programs in metals rapid prototyping R&D. The Japanese focus seems to be on photopolymers because of the superior accuracy of those systems.

REFERENCES

Agarwala, M., et al. 1995. Post-processing of selective laser sintered metal parts. *Rapid Prototyping Journal* 1:36-44.

Greulich, M., et al. 1995. Fast, functional prototypes via multiphase jet solidification. *Rapid Prototyping Journal* 1:20-25.

Nakagawa, T. 1979. The manufacture of blanking tool by laser processing. *Press Technique* (in Japanese) (Nov.), 12-13.

Nakagawa, T., et al. 1985. Laser cut sheet laminated forming dies: Diffusion bonding. *Proceedings 25th Int'l. MTDR Conf.*, 505-510.

Sites. 1996. This reference designates the companion volume to this JTEC/WTEC report: Prinz, F. B., ed. *JTEC/WTEC panel report on rapid prototyping in Europe and Japan.* Vol. II. *Site reports.* Baltimore, MD: Loyola College. NTIS Report #PB96-199583.

CHAPTER 7

MATERIALS — CERAMICS

Allan J. Lightman

INTRODUCTION

There is considerable interest in the United States in applying rapid prototyping (RP) technologies to the fabrication of ceramic parts, primarily for military or aerospace needs. This interest in RP technologies is driven by the potential applications of high-performance ceramics and the need to find fabrication techniques that will reduce the cost of ceramic parts. Ceramic materials offer performance at both elevated temperatures and in harsh environments. A number of programs funded by the Department of Defense focus on development of production capability for military parts. The technologies developed can transition directly to the commercial sector.

In contrast with the programs in the United States, materials development efforts in both Europe and Japan are focused first on polymers and then on metals. The development of ceramic materials and processes for RP is considered a low priority. Interest in ceramics appears to be only a by-product of ongoing development, with the exception of the EOS RP machine, which builds parts using foundry sand.

APPLICATIONS PROGRAMS

Europe

EOS GmbH of Germany markets the EOSINT S rapid prototyping machine, which fabricates casting patterns directly in sand. The process is a modification of EOS' standard sintering machine, in which a coated refractory sand is used as the powder. The mold information is written using a CO_2 laser that causes the sand particles to adhere by heating and binding their coating. EOS has termed the process "Direct Croning®," referring to the particular refractory sand employed. Molds for complex parts can be built quickly, and castings can be made directly into the sand mold (Fig. 7.1).

Researchers at the Fraunhofer Institute for Applied Materials Research (IFAM) in Bremen (http://www.ifam.fhg.de) have already produced ceramic part (SiC) fabrication using their Multiphase Jet Solidification (MJS) system (Fig. 7.2). Current materials development for MJS is focused on metals, but the system developers have stated that they are considering ceramic materials for future development.

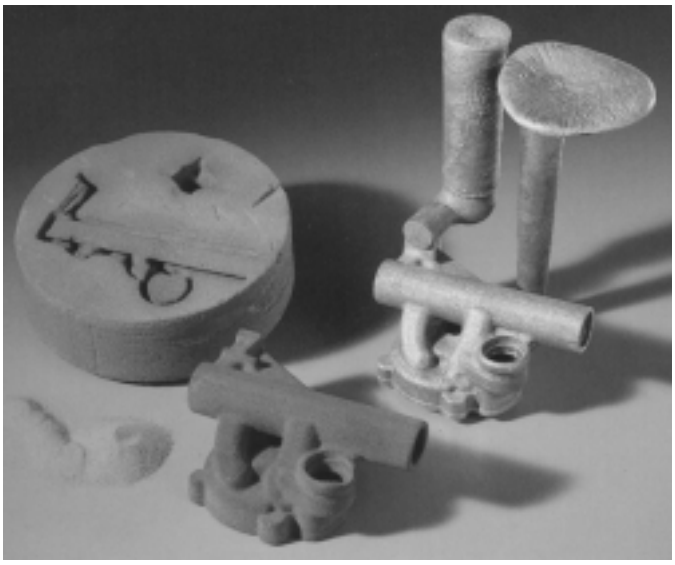


Fig. 7.1. Sand mold, sand positive, and aluminum casting produced within one day (EOS).

Fig. 7.2. Ceramic parts produced by MJS: (left) green parts (tip and SLA test part); (right) sintered parts.

Japan

Researchers at both Teijin Seiki and D-MEC have openly discussed their efforts to incorporate ceramic (glass) spheres within their photopolymers for use in their standard RP stereolithography (SL) machines. The objective is to produce a prototype that can be used as a mold face for a limited number of injection molding operations. The ceramic provides added strength to withstand the molding pressures, and it provides thermal conduction to keep the mold faces from deteriorating rapidly due to the injection of molten plastic. Typically, the mold halves are backed by metal frames with cooling lines. The Teijin Seiki material has been demonstrated to withstand ABS temperature and pressure requirements for at least 22 shots (Fig. 7.3). A D-MEC mold shown informally in 1995 at the Sixth International Conference on Rapid Prototyping (Dayton, OH) evidenced use at elevated temperature; no information was available on the longevity of the mold. Introduction of ceramic considerably raises resin viscosity, creating problems for many of the leveling systems used by vendors (viscosities as high as 49,000 cps have been mentioned by Teijin Seiki engineers).

This high viscosity restricts the loading concentration used and the range of dimensions of the particles, since both higher concentrations and smaller-diameter particles (loaded to a constant percent) result in increased viscosities.

Fig. 7.3. Direct RP mold faces backed with a steel frame. Ejection pins can be seen in the core.

Professor Nakagawa of the University of Tokyo mentioned to JTEC/WTEC panelists that ceramic parts are typically fabricated in plaster molds, usually using slip casting. He recently developed a nonaqueous carrier for the ceramic, which does not require a porous mold. Nakagawa successfully cast ceramic into a rubber mold, which opens the possibility of having reusable molds that can be created rapidly using an RP master.

United States

In the United States, universities, industries, and government laboratories have been actively working with ceramic materials. Several licensees are commercializing aspects of MIT's "Three-Dimensional Printing" program (http://web.mit.edu/afs/athena/org/t/tdp/www/home.html). These include Soligen, which offers the "Direct Shell Production Casting" machine. The machine "writes" patterns for molds directly into ceramic powder using a binder dispersed via an ink-jet printer head. The resulting pattern is then cleaned of loose powder and sintered to provide a shell into which metal can be cast. A host of other processes are under development, most of which are tied to modifications of existing commercial systems. Some of these efforts are mentioned below.

Selective laser sintering of ceramic powders and fusing of coated ceramics are being investigated by DTM and the University of Texas (http://lff.me.utexas.edu). Both Lone Peak Engineering and the University of Dayton are investigating production of ceramic tapes and use of these tapes in the laminated object manufacturing (LOM) environment. In addition, the University of Dayton (http://www.udri.udayton.edu/mat_eng/rpdl.htm) is extending this process to ceramic composites using both chopped and continuous fiber reinforcement in its tape systems. Ceramic loading of photopolymers for use in stereolithography systems is being developed at the University of Michigan. Argonne National Laboratories (http://www.anl.goc/ITD/rapid.html) and Rutgers University (http://www.caip.rutgers.edu/~jumalata/sff-

others.html) are developing ceramic-loaded filaments that will be compatible with fused deposition molding systems, similar to the multiphase jet solidification (MJS) system being developed in Europe. Case Western Reserve University is developing the CAM-LEM system, which utilizes ceramic material delivered in sheet format. Each material layer is cut by a 5-axis laser cutter that shapes the edge to match the slope of the part at every location. The layers are then robotically stacked and sintered to form the part. Other efforts include the program at Stanford Research Institute to develop a filled photopolymer.

The U.S. effort encompasses the development of ceramic molds for casting and the fabrication of both monolithic and composite ceramic parts. The particular ceramics under study include lower-temperature oxides and the higher-temperature materials such as SiC and AlN. RP fabrication of ceramic components could potentially open a variety of application areas that heretofore have been cost-prohibitive.

CONCLUSIONS

The United States leads efforts to develop ceramic materials and processes for RP applications. European and Japanese programs focus on specific applications of ceramic materials. The European application is directed toward the creation of sand molds for metal casting. In Japan the thrust is to toughen polymer mold faces so that RP molds can be directly used for plastic injection. The Europeans have indicated their interest in direct manufacture using ceramic materials through the MJS system, but at the time of the panel's visit there was no activity in this area. There are many programs underway in the United States leading to the fabrication of ceramic parts for direct use and for use as ceramic molds to cast metal parts. The more substantial U.S. interest may be attributed to the military and aerospace applications that require these high-performance materials and to the strengths of these industries in the U.S. economy.

REFERENCES

All references in the text of this chapter are given to World Wide Web sites where the denoted technology is described. The websites provide descriptions of the processes employed and examples of the results achieved.

CHAPTER 8

CAD AND INTERFACES

Michael J. Wozny

INTRODUCTION

The systems aspect of rapid prototyping (RP) is one area where the differences between efforts in the United States, Europe, and Japan are particularly evident. The RP system, as shown in Fig 8.1, extends beyond the solid freeform (SFF) machine itself and includes machine pre-operations, such as the preparation of geometry data, and machine post-operations, such as curing, support removal, and cleaning.

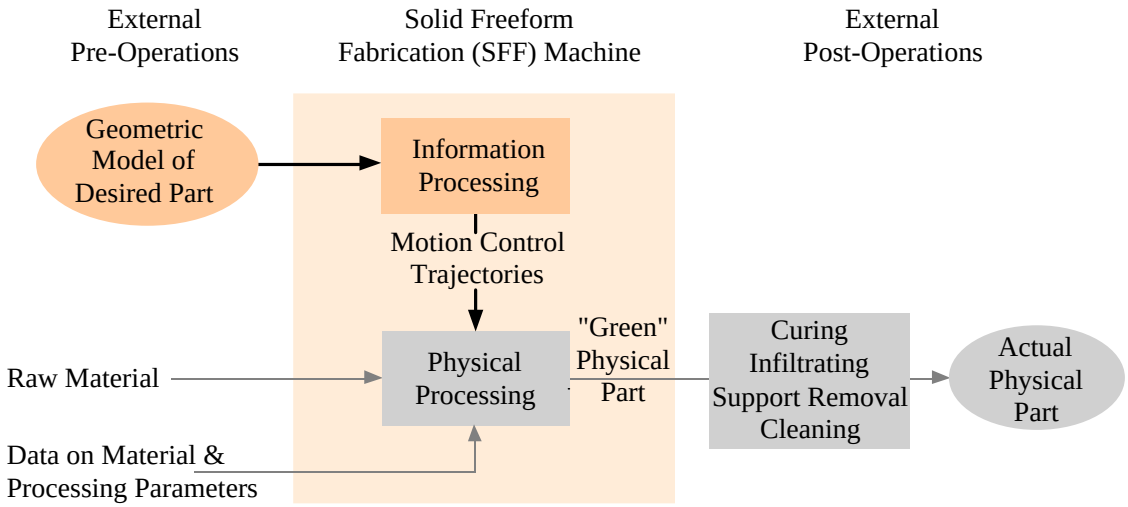


Fig. 8.1. The rapid prototyping "system."

The focus in this chapter is on those system elements that affect the shape of the part: the SFF machine's data interfaces (2D, 3D) to the external geometry-creating environments (MRI, CAD); the math (triangles) and data (STL file) representations of the geometric model; and the subsequent modifications of and additions to the original geometric model, in terms of orientation, scaling, nesting, distortion compensation, and support structures, to accommodate process-specific characteristics. This prepared model is used to generate the appropriate motion control signals in the equipment (slicing, scanning), which in turn drive portions of the

physical fabrication process. Topics such as input material data and process parameter data are part of the process controller and not discussed in this report. Also not discussed here are input data about tolerances, features, and assembly configurations, since the JTEC/WTEC panel observed no specific project dealing with such research issues.

SYSTEMS OVERVIEW

Fig. 8.2 shows the five basic RP system elements that affect shape: (1) data creation, (2) common data exchange format, (3) model validity and repair, (4) compensation, and (5) support structures.

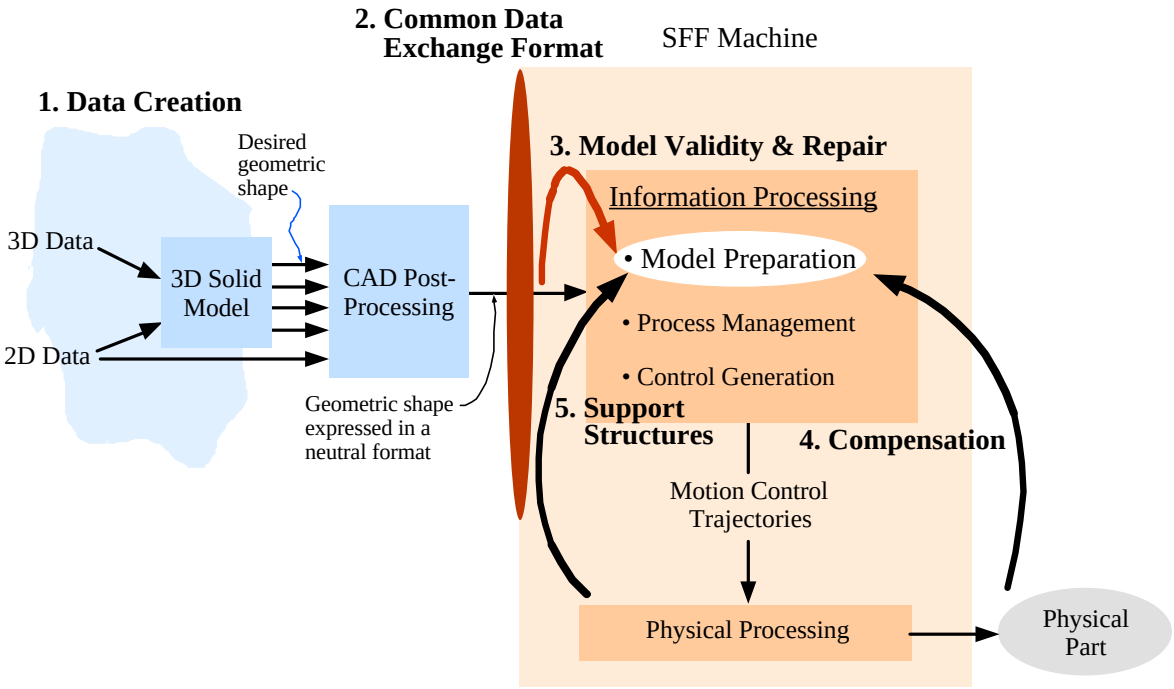


Fig. 8.2. RP elements affecting shape.

Data Creation

The first step in the overall RP process is the creation of geometric data, either as a 3D solid using a CAD workstation, or as 2D slices using a scanning device. In either case, the data must represent a valid geometric model; namely, one whose boundary surfaces enclose a finite volume, contain no holes exposing the interior, and do not fold back on themselves. In other words, the object must have an "inside." Nonmanifold conditions such as zero-thickness dangling surfaces or more than two surfaces meeting along a common edge, among others, are not allowed (Weiler 1986).[1] Even thin shells have finite volumes. The model is valid if for each point in 3D space the computer can determine uniquely whether that point lies inside, on, or outside the boundary surface of the model, and if the region around the point (neighborhood) is "well behaved." This fundamental property makes possible the automatic geometric manipulation operations that give SFF its appeal as an automated process.

[1] Weiler 1986 is the original reference. Papers on the subject have appeared in the IFIP WG5.2 series of volumes on geometric modeling in Wozny et al. 1988, Wozny et al. 1990, Turner et al. 1991, and Wilson et al. 1992.

If 2D contour data are sent directly to the SFF machine, the information implicit in the description must be sufficient to stitch together a valid 3D volume.

Common Data Exchange Format

For reasons of competitiveness, targeted markets, and performance, CAD systems utilize a variety of geometric mathematical forms and data formats. SFF machine vendors accommodate this variety by requiring that all external input geometric models be expressed in a neutral format. CAD vendors are responsible for providing CAD post-processors that translate their internal CAD representations to this common format.

Model Validity and Repair

To be more precise, CAD post-processors actually approximate the vendors' internal CAD geometric forms (e.g., B-splines) with a simplified mathematical form (triangles), which in turn is expressed in a specified data format: STL. Unfortunately, this approximating operation, if not done precisely, sometimes introduces undesirable geometric anomalies, such as holes or overlapping portions in the boundary surface. Consequently, most SFF machines have software to check the input model to ensure it is a valid solid, that is, it is a well-behaved, closed, and bounded model with a finite interior. If this is not the case, then capabilities are needed to repair the model.

Given a valid model, a series of geometric operations must be performed on the model (model preparation) to ensure that the physical part will meet the input specifications. For example, the model needs to be oriented and scaled for the SFF machine workspace. The orientation depends on factors relating to surface quality, build time, support structures, downstream processing characteristics (shrinkage, curling, distortion, resin flow), and part tolerance, among others (Frank and Fadel 1994; Thompson and Crawford 1995). The nesting (Beascoechea 1995, 1996) of many parts in a single build chamber and the building of assemblies concurrently are also considerations.

Compensation

The model shape may need to be altered to compensate for anticipated downstream physical anomalies introduced during fabrication, such as shrinkage, warpage, curl, and deformation. Most compensation today is coarse and usually left to an operator's intuition, gained by trial and error. The status of predictive analytic models is discussed later.

Support Structures

Support structures are needed in liquid-based processes to prop up overhanging portions of the 3D part, to attach the part to the workspace platform, and to internally buttress hollow parts. Parts and supports may need drain holes. Support locations for overhangs can be determined by checking the direction of surface normals and by z-axis projections of the model. Software exists to automatically generate support structures that attempt to use the least possible amount of material. Powder- and sheet-based processes use the surrounding unprocessed material for support. Even in these latter processes, the Japanese would like to shorten the time required to remove unprocessed support material and clean the part to high surface quality. The cost of data preparation and post-processing can amount to two-thirds of the total cost of building a part (Dolenc and Mäkelä 1995).

For very precise parts with many thin protrusions, the compensation and support structure generation operations may need to be iterated, because the support may distort the previously compensated part.

To obtain the necessary motion control trajectories to drive the actual solidification mechanism, the prepared geometric model is sliced into layers of possible different thicknesses, and the slices are scanned into lines (if required), mimicking in reverse the layer-to-layer physical building process (Rock 1991; Dolenc and Mäkelä

1994; Suh and Wozny 1994). The scanned lines determine when a laser beam or some other solidifying agent is turned on or off. The layer thickness determines the amount to raise or lower the part and/or the container for recoating.

Using a manufacturing interpretation, Otto et al. (1995) categorize SFF software as the following types: (1) design (original part); (2) computer-aided process planning (part orientation, scaling, nesting, support design, compensation); and (3) computer-aided manufacturing programming (slicing, commands, and controls).

Ultimately, more sophisticated control strategies based on process sensor feedback loops are desirable, but this is still a topic of research.

MAKING THE TRANSITION TO 3D SOLIDS

3D solid modeling is a relatively new concept to design and manufacturing — less than 30 years old. Its widespread use in practice is even more recent, made possible by the large increases of the past 15 years in the information processing power-to-cost ratio. On the other hand, engineering drawing using paper and pencil has evolved over 150 years. Although designers have migrated to solid modeling because analysis is more easily handled, manufacturing engineers by and large still rely on drawings. The reason is more complex than that it requires a *pro forma* change in the way engineers view parts. An engineering drawing is a sophisticated language for building things and contains many nongeometric elements like tolerances, notes, and procedures that are meaningful to production. A solid model is simply a geometric representation of shape.

It is therefore not surprising to find manufacturing-oriented companies, both large and small, changing only slowly to 3D solid modeling. The JTEC/WTEC panel found this to be particularly true in Japan, where use of 3D solids was estimated to be between 3% and 20%. Whatever the actual percentages, it is apparent that a sizable number of RP users in Japan are not utilizing 3D solids at present. On the other hand, solid modeling for RP is used widely in Europe, but still not as extensively as in the United States, where the solid model is seen as a key element in the next-generation design and manufacturing data representation that will supersede drawings, because it will be able to support automated processes.

The reason for the perceived slow adoption of 3D solids in Japan is not entirely clear. One answer may be that the panel did not see a suitable cross-section of activity in large user companies because their RP technology was employed in the development of new proprietary products. Another reason may be that SFF is still too embryonic and relatively imprecise to attract serious attention across a large segment of Japanese industry. The current benefits of RP technology are perhaps perceived to be too small when compared with the fast turnaround and high quality achieved by Japanese NC (numeric control) machining technology, which is the best in the world. NC parts are produced directly from 2D drawings today.

Rapid prototyping will come into its own when the industry goes beyond making parts faster and starts producing parts not possible by any other means. Sachs et al. (1995) give a relevant example dealing with the creation of cooling channels that conform to the shape of the injection molding tooling, as opposed to the traditionally machined straight channels. The conformal channels give precise temperature control of the molding cavity throughout the process cycle and reduce the part production cycle time.

It is a significant problem in Japan that most 2D part drawings must be recreated with 3D data before proceeding with RP, since much of this work is done manually.

Table 8.1 lists comments concerning this issue that the JTEC/WTEC panel collected from various Japanese hosts, primarily at the service bureaus. When the JTEC/WTEC team mentioned such comments to MITI representatives, the response was that they recognize that this is a problem and they would like to see change, but there are no programs specifically aimed at accelerating the acceptance of 3D solid modeling. Several hosts noted, however, that this and other RP topics may be addressed within the large supplementary budget

programs recently enacted by the Japanese government, with the most likely candidate being a major CALS (Commerce at Light Speed) program dealing with information integration in manufacturing.

Table 8.1
1995 Company Estimates of 3D Solid Modeling Use in Japan

RP COMPANY OR SERVICE BUREAU	USE OF 2D VERSUS 3D
Tokuda Industries	80% of customers provide 2D CAD files that must be recreated in 3D
INCS, Inc.	90% of customers provide CAD files: - 55% 3D data (not necessarily solids) - 35% drawings - 10% others In 1993, creating/recreating 3D data represented 50% of total production time
Kyoden Co.	In 1993, 100% of work had to be converted from 2D to 3D In 1995, 70% of customers submitted 2D files By 2000, expect 50% of small companies and 100% of big companies to use 3D
Shonan Design Co.	50% of its work done on 2D CADAM; 20% on Pro/Engineer; 30% on CATIA

The panel's hosts also predicted dramatic changes in the future. They relate that Japanese industry has realized the strategic value of 3D solids; at the time of the JTEC/WTEC visit to Japan, plans were already in place to transition to 3D CAD, with large companies expected to begin the shift within two years.

Few comments surfaced from the European site visits that expressed concern about the issue of 2D drawing versus 3D solid modeling. Instead, the issues in Europe seem to be related to cost and ease of use.

MAKING 3D SOLIDS-CREATION EASIER

Comments from users in Japanese companies, such as those in Table 8.2, express concern that 3D solids-creation takes too long and needs to be simplified, both from the viewpoint of migration from 2D, as well as original creation in 3D. Issues include training and reduction of learning times; software aids for simplifying 3D use; software aids for easing the transition from 2D; company-wide integration of 3D; and targeted applications, especially those involving small companies.

As Table 8.2 shows, Japanese organizations and researchers are taking a variety of approaches in addressing these issues. Hino Motors reduced learning times by simply changing its CAD system. Nakamura Pattern Making Company adapted easily to an RP system based on wood, a material with which its pattern makers have a lot of experience. In fact, company owners hold that effective use of SFF is not possible without profound understanding of the material. Meiko developed a CAD system, JCAD3, intended only for jewelry design, that is easy enough to use that the jewelry industry's designers should be able to use it with little CAD experience. D-MEC plans to develop software to help users convert 2D drawings to 3D solids. No system will do this automatically, since drawings are sometimes incomplete or ambiguous, lack associativity among views, or do not follow geometrically precise conventions in generating auxiliary views.

Researchers are also addressing the ease-of-use issue. Professor Fukuda at Tokyo Metropolitan Institute of Technology is developing tools that will create and modify models more intuitively at early design stages. He says his system, which can build 3D models from 2D slices, is very easy to use. Professor Fukuda is also

working on a virtual reality (VR) tool for facilitating design modification. His goal is to have a designer produce a prototype part, then be able to manipulate it with data gloves (Fukuda would like to use a soft putty-like material), and feed back those changes immediately to the CAD environment via sensors. Touch cues are an important designer feedback mechanism. Data gloves with force feedback will play an important role in design in the future.

Table 8.2
Japanese Views on Using 3D Solids

COMPANY/INSTITUTE	COMMENTS
Olympus Optical Co.	Preparing 3D CAD data takes a major portion of time Constitutes a major barrier to use of rapid prototyping
Omron	Limited 3D CAD experience is a major barrier Needs to be easier for design and tool engineers to use
Toyota Motor Corp.	Preparing data for RP takes too long
Shonan Design Co.	"Section" thinking in large companies: designers accept 3D CAD, but tooling engineers use 2D drawings 5% of companies have 3D CAD/CAM common data
Hino Motors	Replaced its CAD system to reduce learning times Widespread use of 3D CAD in company in 2-3 years
Meiko Co.	Produces and markets its own easy-to-use CAD system Jewelry industry has little experience with CAD
Nakamura Pattern Making Co.	Adopted 3D CAD easily due to long experience building 3D patterns
D-MEC	Designers need help to migrate from 2D to 3D systems
Tokyo Metropolitan Institute of Technology (Prof. Fukuda)	Need CAD systems that support intuition at early design stages VR coupled with CAD and RP supports intuition and facilitates modification

Although better analytical models will enable greater use of simulation and VR, physical prototyping will not vanish. In fact, a physically prototyped part of the future may contain a specially instrumented computer-sensing system housed in the geometric package. Clearly, aspects of today's physical prototyping will evolve into the next-generation manufacturing machines.

INTERFACE FORMATS

The formats used by SFF machines to accept external geometry consist of a mathematical representation of the geometry and a data description in a file.

Mathematical Representation

The boundary surface of a solid can be expressed in a variety of geometric forms: Bezier, nonuniform rational B-spline (NURBS), Coons patch, Gordon patch, planar patch, cyclide, and other blending surfaces, lofting surfaces defined by specific procedures, and implicit forms, to name just a few. For each form it accepts, the SFF machine must maintain a separate set of geometry manipulation routines or utilities, even in cases where the form is a special case of another, if speed is an issue. (There is a time penalty incurred when slicing simple triangles with a generalized complex slicing algorithm designed for NURBS surfaces.) This means that many of the CAD geometry utilities that already exist in the different vendor CAD workstations must be

duplicated in the SFF machine. The need for duplication is further exacerbated by the fact that CAD vendors generally do not make public all aspects of their internal geometries.

The ideal compromise, and the one often followed today, is to have SFF machines accept one common geometric form — thus needing only one set of slicing and other geometric utilities — and shift to the CAD vendors the burden of translating their internal, sometimes proprietary, math forms to this accepted common form. Conceptually, the problem reduces to one of approximating by a single geometric form all other geometric math forms, as well as their intersection curves, trim curves, and blends — hardly an optimal solution.

Triangular Facets

What "common" math form to use? One choice is the most general math form possible, which will be discussed later in the section on the STEP standard. The other extreme is to choose the simplest of all the geometric surface forms, the triangular element. (Some argue that slices are a simpler and more flexible representation.) The triangular approximation consists of sampling the original surface and connecting the surface sample points with triangles. The simplicity of the triangle geometry is offset by the huge numbers of very small triangles needed for a good approximation, and the opportunity for numerical and other approximation errors (some triangles may degenerate to lines).

The process of approximating a surface by triangular facets, sometimes referred to as tessellation, is used extensively in computer graphics, where special integrated circuit chips have been designed to perform this function. Triangular approximations of smooth surfaces work well for color rendering and shading on graphic displays, because the surface is continually subdivided until the triangles are smaller than a screen pixel, and then each triangle is color-blended across its edges to give the appearance of a smooth shaded surface. Unfortunately, slope discontinuity across the edges of adjacent triangles cannot be disguised so easily in physical parts, and this has downstream processing ramifications.

Data Representation

The simplest scheme for a data format is to represent the solid as a sequence of surfaces. A surface is represented as a sequence of triangle elements, with no regard to order or topology. A triangle element is represented as a sequence of its three vertices and its outward (from the surface)-pointing normal vector, defined according to the right hand rule by the order of the vertex sequence (Fig. 8.3). This representation, along with its data types, delimiters, and other file information is called the STL format, introduced originally by 3D Systems, Inc., in 1988. It is the *de facto* standard for transferring solid geometric models to SFF machines.

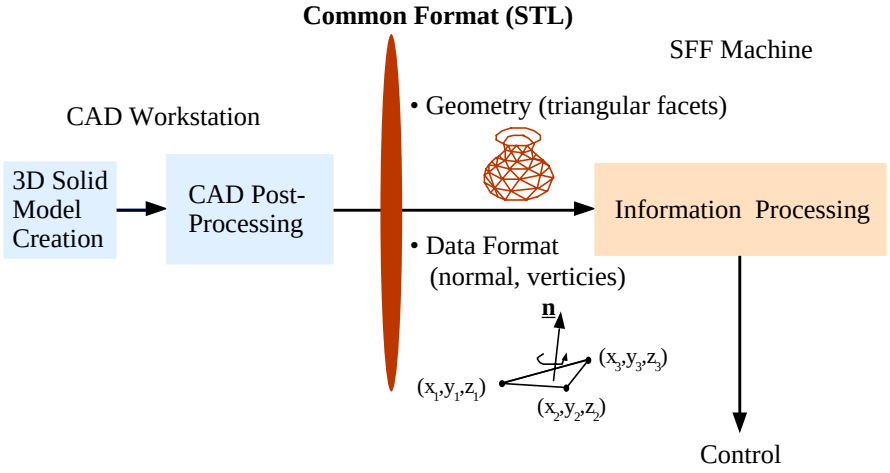


Fig. 8.3. Geometry form used in STL format.

Although many SFF machine vendors offer their own formats (summarized in Fig. 8.4 on p. 80), they all accept STL. Since 3D Systems was the first and remains today the major vendor in the marketplace, its format will continue to dominate. The small enhancements in format offered by others will not tilt the balance. Based on the evolution of CAD formats, the key enabler of change will be a motivated and vocal user community.

CAD Solid Modelers Accepted by SFF Machines

Table 8.3 lists the CAD modelers being used at the sites visited by the JTEC/WTEC panel. As one would expect, many of the solid modelers popular in the United States are also popular in Europe and Japan. The reason is simply that U.S. CAD vendors dominate the commercial market. Whereas many U.S. companies now use vendor-supplied CAD systems, Japanese companies continue to develop proprietary systems (or portions of systems). Most European companies use commercial modelers, except for some large companies like Daimler Benz.

Table 8.3
CAD Solid Modelers That Interface with SFF Machines

CAD Solid Modeler *	Company
Pro/Engineer	Parametric Technology
CATIA	Dassault Systèmes
CADDS	Computer Vision
CADAM	Dassault Systèmes
I/EMS => Solid Edge	Intergraph
Unigraphics (parasolid)	EDS
ME30 & PE/Solid Designer	Hewlett-Packard
AutoCAD	Autodesk
DesignBase	Ricoh
Fresdam	Sony
Caelum	Toyota
I-DEAS	Structural Dynamics Research Corp.
Camand (surface)	Camax Manufacturing Technologies
CAM Tool	
MacSurf (surface)	Denken and Autostrade
ZYRCO	Daimler Benz
DUCT	Delcam (UK)
Euklid	Swiss

* Most names are registered trademarks

The desire to develop proprietary CAD and RP software is reminiscent of the “reincarnation of the wheel” phenomenon, which is characteristic of fast-moving fields. It was certainly true in commercial CAD during its rapid growth in the late 1970s and early 1980s. CAD may be used as an example to illustrate the dynamics. Initially, large technically based companies developed their own internal CAD systems because their specific internal needs were not being met by the emerging commercial vendors. Using their formidable state-of-the-art internal expertise in applications and computers, these companies were able to create CAD environments that not only went well beyond the capabilities of commercial systems, but also were tuned to their internal needs. However, when these CAD systems became operational, the general tendency was to scale back further enhancement because, after all, the system is only a means to an end and not the main product of the company. Meanwhile, the commercial CAD vendors continued to innovate and ultimately

surpassed the capabilities of the user companies, causing senior management to abandon aging internal systems for state-of-the-art commercial systems.

This cycle continues to repeat itself. As the CAD vendor's application base continues to grow and diversify, its support has to harmonize the needs of a larger application base. Since the vendor can no longer dedicate sufficient resources to company-specific enhancements and meet the company's rigid time schedules, the company launches a new internal development effort to create its next-generation CAD environment aimed specifically at its current needs.

The trend in rapid product development today is toward a broad system of many integrated functions. CAD is but one cog in this big product development wheel. Consequently, enhancements in CAD are judged not in isolation, but in terms of their effect on overall system functionality, throughput, and stability. A new geometric engine may not be useful if it means redeveloping existing geometric utilities, scrapping the database system, and launching a major training program. Ultimately, such considerations will be necessary for those RP systems used in engineering and manufacturing.

Today, virtually every commercial CAD vendor provides a CAD post-processor for translating internally represented CAD solid models into faceted solid models for SFF machines. Additional modelers that provide STL include Aries Concept Solids from Aries Technologies; Bravo3 from Applicon; CADKEY from Cadkey, Inc.; and the French modeler EUCLID from Matra Datavision. A number of PC-based 3D modelers originally developed for 3D graphics applications now offer STL output capability.

Standard for the Exchange of Product Model Data (STEP)

Although many agree that the STL format leaves much to be desired, there is no unanimity on its replacement (Dolenc and Mäkelä 1995; Jamieson and Hacker 1995). Since there is no single all-encompassing general math form that includes *all* other practical geometric surfaces as special cases, then it makes sense to focus on those math forms that support a large application base. The evolving STEP standard for the exchange of product data, based on NURBS geometry, is the most promising candidate, because of its growing acceptance and use in engineering and manufacturing applications.

NURBS geometry was originally promoted and developed by the aircraft industry, specifically by Boeing, because conic sections, which are very important in the aerodynamic design of airplanes, are represented exactly by NURBS. With its great flexibility and power, however, NURBS has disadvantages as well: it is more difficult to master; pathological and practically nonrealizable surfaces are easily generated; and some theoretical aspects are still thorny. Regardless, NURBS has caught on and is rapidly becoming the most widely used surface form, including the computer graphics standard, PHIGS (Programmers Hierarchical Interactive Graphics System).

In the United States, the CAD community has been developing standards for exchanging data among CAD systems since 1979 when Boeing, GE, and NIST (National Institute of Standards and Technology, then known as the National Bureau of Standards) joined forces to lead a national effort to develop a neutral file format for representing engineering drawings. The effort led ultimately to IGES (Initial Graphics Exchange Specification), which became a U.S. national standard in 1981. See the U.S. Product Data Association (http://elib.cme.nist.gov/nipde/) and STEP Tools, Inc. (http://www.steptools.coml) web sites for details. The current version, IGES 5.2 transcends its original manifestation as a standard for exchanging 2D graphical drawings and includes 3D surfaces and solids. Similar efforts in Europe led to the German DIN 66301 standard, VDA-FS (Verband de Automobilindustrie 1987, http://www.serv.net/tms/vda_over.html), and the French AFNOR Z68-300 standard, SET (Standard d'Échange et de Transfert).

All of these CAD standards efforts are now being superseded by STEP,[2] a much more extensive data exchange standard that will eventually extend beyond product data and include process and resource data. The first phase of STEP was approved in late 1994 as international standard ISO 10303 by the International Standards Organization (ISO) (http://www.igd.fhg.de/www/igd-a2/hyperstep/iso-10303/gen.htn and http://www.scra.org/pdesinc.html). Most CAD vendors are committed to supporting STEP. (One can think of IGES as specifying a neutral *flat* file format, while STEP specifies the *associativities* of a neutral database.) The STEP standard provides extensibility to many application domains through a structure called "application protocols." Each application domain has its own application protocol, with substantial sharing of common core functions.

There is strong interest in developing a STEP application protocol for exchanging CAD data with SFF machines. In Japan, Professors Kishinami and Kimura (http://www.cim.pe.u-tokyo.ac.jp/index-j.html), who have interests in systems aspects of rapid prototyping, are also deeply involved in STEP activities. Preliminary work on a STEP application protocol for SFF machines was begun in 1993 as part of the Rapid Product Realization project in the international Intelligent Manufacturing Systems (IMS) program, led by United Technologies in the United States, Daimler Benz in Germany, and other companies in other countries. See IMS Test Case #6 1994 (January and June), and Aubin (1994). SFF standards continue to be promoted in the United States by the Rapid Prototyping Association of the Society of Manufacturing Engineers (http://www.sme.org/memb/rpa.html), NIST, and the DOE Sandia National Labs. Gilman and Rock (1995) propose to integrate more closely into the design process using STEP as the vehicle of integration.

2D Slice Data

For many reasons, 2D slice data is a viable format. Some believe a 2D contour representation is more basic than a 3D solid model. The founders of one German company, Fockele and Schwarze (1994), believe that the 2D contour representation allows their company to build bigger and more precise parts. Others suggest it is easier to work with. Management of the Belgium software company Materialise (http://www.materialise.com/technic/contour.html) takes this position: "At the primary level, each RP machine operates on the basis of stacks of 2-dimensional drawings. 2D contour software enables the user to work efficiently with this data stream, thus solving special problems and enabling special applications.... By tackling the interfacing problem at the contour level, contour software is able to solve all problems with bad STL files." Finally and most importantly, 2D data from medical scan devices represent the tip of the iceberg for a vast biomedical field that promises to be a key application area for RP.

European activity in 2D formats is motivated in good measure by biomedical applications (implants, operation planning), but also by reverse engineering applications utilizing laser and other scanning devices.

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[2] The U.S. Product Data Association (US PRO) has been granted distribution rights by the American National Standards Institute (ANSI) to reprint, market, sell, and distribute Draft International Standards (DIS) and International Standards (IS) of ISO 10303 and 13584 within the United States (US PRO; P.O. Box 3310; Gaithersburg, MD 20885; FAX 301-926-8730). Standards of interest here are as follows:

A. ANS US PRO/IPO-100-1993. IGES 5.2, Initial Graphics Exchange Specification, Nov. 1993.

B. ANS US PRO/IPO-200-1994. Product Data Exchange using STEP (PDES): Initial release includes parts (which can be ordered separately)

1. Overview and Fundamental Principles
11. The EXPRESS language Reference Manual
21. Clear Text Encoding of the Physical File Exchange Structure
31. Conformance Testing Methodology and Framework: General Concepts
41. Integrated Generic Resources: Fundamentals of Product Description and Support
42. Integrated Generic Resources: Geometric and Topological Representation
43. Integrated Generic Resources: Representation Structures
44. Integrated Generic Resources: Product Structure Configuration
46. Integrated Generic Resources: Visual Presentation
101. Integrated Application Resources: Draughting
201. Application Protocol: Explicit Draughting
203. Application Protocol: Configuration Controlled Design

Technical interests range from general boundary curve forms (beyond polylines) to more flexible file structures. Rather than tessellate a surface and then slice the tessellated surface, why not slice the original surface (direct slicing) and then approximate the contour curves with polylines? Some feel this process reduces error, produces better surfaces, and results in smaller files (Ganesan and Fadel 1994; Vuyyuru et al. 1994; and Jamieson and Hacker 1995). German companies Fockele and Schwarze (1994) and CENIT GmbH (http://www.catia.ibm.com/html/clog407.html) use direct slicing.

The requirements for a flexible and vendor-independent format led to the development of the Common Layer Interface (CLI) format by a consortium of European countries organized under the EEC research program Basic Research in Industrial Technologies for Europe/European Research on Advanced Materials (BRITE EuRAM 1994). The goal of CLI was a flexible format that applies to all RP technologies, permits user-specific data (such as patient orientation in CT scans), and allows data transfer among a wide range of applications. User-specific data is included in the header section. The geometry section consists of an ordered (ascending) sequence of layers and their respective heights. The boundaries (outside, plus holes) of each layer are defined by closed polylines, with the "inside" or "material" side always on the left as the polyline coordinates are traversed. CLI supports both ASCII and BIN formats (http://www.cranfield.ac.uk /aero/rapid/CLI/cli_v20.html). Its first major application area is medical scan data.

The CLI format is now being supported by the European Action on Rapid Prototyping (EARP). EOS's (Electro-Optical Systems) layer data exchange software in EOSOFT is based on the CLI format. Materialise offers a range of software for RP, including software to generate parts directly from CT (computed tomography) and MRI (magnetic resonance interferometry) scans. Materialise's MIMICS software interpolates data from medical scanners, as described later in the section on RP Software.

There is still some concern that CLI (also the 3D Systems slice format, SLC) is still not flexible enough to be a standard (Dolenc and Mäkelä 1995). CLI seems to be biased toward fluid-based processes and dominated by medical scan data applications. An experimental data exchange format proposed by Dolenc and Mäkelä (1992), called Layer Exchange ASCII Format (LEAF), addresses these and other shortcomings such as flexibility, loss of information, lack of user control, ambiguity, impractical assumptions, and process dependency. LEAF is an experimental tool for researchers to promote standardization and is being developed further by researchers at the Fraunhofer Institute for Manufacturing Engineering and Automation in Stuttgart.

Daimler Benz' ZYRCO CAD software is compatible with CLI and STL, but the company prefers STL. Fockele and Schwarze, on the other hand, builds 3D parts from contours.

The Japanese are using the Hewlett-Packard Graphics Language (HPGL) format for representing 2D slice data. HPGL is the *de facto* standard for 2D plotting, where the data is represented in a vector format: start point coordinates, end point coordinates, pen up/down. INCS is developing software that interpolates and smoothes the CT slice data into an STL model for use in maxial facial reconstruction surgery.

SLC is 3D Systems' contour data format for importing external slice data, and SLI is the company's machine-specific 2D format for the vector commands that control the laser beam.

The Cubital Facet List (CFL) format is based on a polygon-based representation consisting of n-sided polygons that can have multiple holes (Cubital, Ltd. n.d.). The format avoids redundant vertex information and maintains topological consistency. CFL consists of a header and fields containing the total number of vertices (points) and facets in the object, a numbered sequence of vertex coordinates, numbered facets (with number of holes), and pointers back to their respective vertices. An example is given in Fadel and Kirschman (1995).

Fig. 8.4 summarizes the various 2D and 3D formats being used today in Europe and Japan.

Virtual Reality Modeling Language (VRML)

The Bremen Institute for Industrial Technology and Applied Work Science (BIBA) has opened a web dialog on replacing the STL format with the Virtual Reality Modeling Language (VRML) format (http://www.biba.uni-bremen.de/users/bau/s2v.html). VRML is an evolving standard for describing multiparticipant interactive three-dimensional scenes networked via the global Internet and hyperlinked with the World Wide Web (http://sdsc.edu/vrml/ and http://vrml.wired.com/). VRML is based on the Open Inventor ASCII File Format from Silicon Graphics, Inc., which supports descriptions of computer graphics 3D scenes with polygonally rendered objects, lighting, materials, ambient properties, and realism effects (http://vrml.sgi.com/moving-worlds/). VRML, in the near term, extends this base to support multiuser network interaction, animation, and scripting.

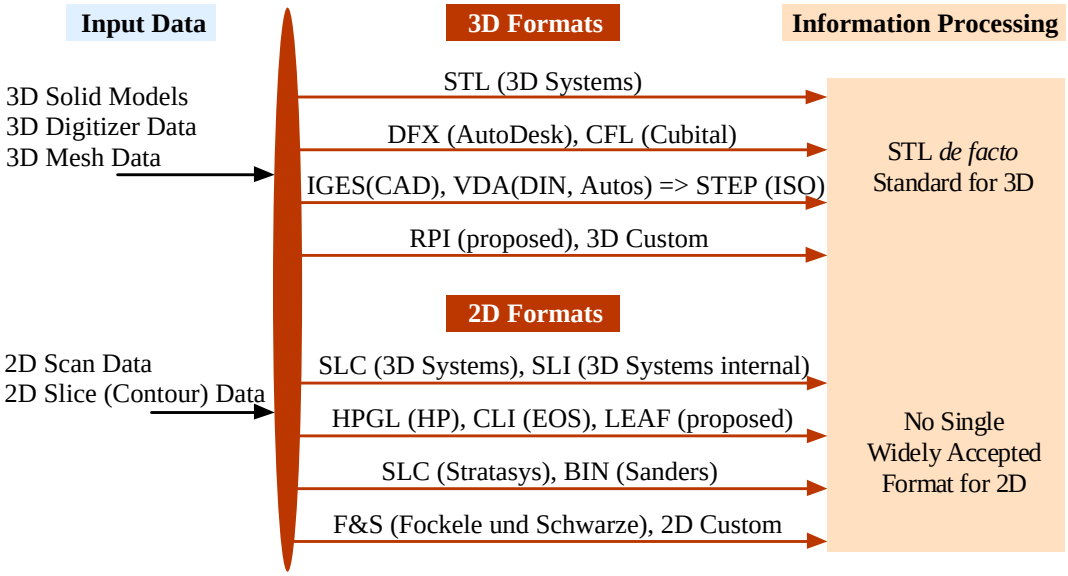


Fig. 8.4. Data exchange formats for SFF machines.

Advocates of abandoning STL point out that VRML deals with the bigger picture: the 3D extension of the World Wide Web, the future 3D telecommunication and networking standard, which could also become the standard interface for all "3D hardprint" tasks, with formats for storing and viewing with a 3D web browser before printing. Advocates claim that the adoption of VRML would make RP more accessible globally. VRML 1.0 (http://vrml.wired.com/vrml.tech/vrml10-3.html) is based on facets, so it accommodates STL files as well as accommodating AutoCAD DXF and parts of IGES, among others.

Some RP research, for example, by Baily at the San Diego Supercomputer Center, deals with "telemanufacturing" issues (http://www.sdsc.edu/EnablingTech/Visualization/TMF/tmf_intro.html).

VRML will work well for describing the network-based objects in a 3D scene involving interaction, animation, or simulation, because VRML is a direct extension of interactive computer graphics. True network interaction and seamlessness will ultimately require Java-like concepts. VRML today provides a geometry-viewing capability but has not addressed engineering needs such as the creation of very complex geometry and the ability to use it in other analyses. (Future versions of VRML are expected to include NURBS, but today, such geometry creates a heavy processing load.) This is where STEP and other engineering network projects, like National Industrial Information Infrastructure Protocols

(http://www.niiip.org/) or Computer-Aided Manufacturing Network (CAMnet) (http://ce-toolkit.crd.ge.com/camnet/conops/conops_5.html) in the United States play an important role for engineering and manufacturing.

The engineering and manufacturing applications segment of RP will not be the major segment of the future RP market, and not necessarily the primary technology base for the mass market. In the past two decades, much of the innovative computer technology (PCs, RISC architectures, small high-density disks) and interfaces (Xerox PARC, Apple) that made computer technology accessible by the masses evolved from needs at the grass roots (even computer games), not from the needs of large mainframe operations. The same will be true for future 3D Fax technology — it will have to be stand-alone, desktop, cheap, and universal.

Future RP systems for engineering and manufacturing applications will be specialized and at the cutting edge of processing sophistication, because these systems will replace existing manufacturing machines that make functional parts.

Demarcation between SFF Machine Functions and External Geometry Creation Functions

Duplicating CAD geometry manipulating functions in SFF machines preserves the functional independence of the machines from the CAD workstations generating the input data. Model manipulating operations that deal with SFF machine-specific functions, such as orientation, scaling, nesting, compensation, and slicing, need to be dealt with locally by an operator who understands the idiosyncrasies of the SFF process and the properties of the raw material. If, for example, a prototyped part warps or shrinks more than anticipated due to an unforeseen processing imperfection, the operator must have the option to compensate locally and make another run without having to go back to the CAD environment. The need to understand in detail the processing and material properties is even more important when producing functional parts (metals, ceramics, etc.).

If changes in the original design need to be iterated with a series of interim prototypes, then ideally, such incremental changes should retain as much of the originally processed data as possible.

As the RP market ultimately subdivides into focused segments, that portion dealing with producing form parts for viewing should achieve totally automated operation.

MODEL PREPARATION

Model preparation begins with validation of the input model to ensure it is a solid; if it is not, it must be repaired. (Models are corrupted either by designer misunderstandings or inadequate CAD post-processing, as described below.) The valid model is then scaled and oriented with respect to the build chamber, taking into account build direction, build time, surface quality, and potential distortion. Many models may either be merged into a one-build assembly or nested for efficient utilization of the machine and material. The models may need to be compensated to account for downstream shrinkage or deformation. Finally, the supporting structures for overhanging part geometry as well as internal supports are added, if the process requires them. Such structures are often generated automatically in a separate file that is merged with the model file prior to slicing. The generation of control signals starts with slicing the model(s) and then scanning each slice into lines to determine the peripheral contour boundary needed to control the solidification process.

Model preparation consists of three steps: (1) validation and repair; (2) compensation; and (3) support structure generation, as illustrated in Fig. 8.5.

Model Validation and Repair

Any sampling process can introduce geometrical anomalies. For example, if spatial sampling is done too grossly, then small local features and local surface curvatures are lost irrevocably, or if two intersecting surfaces have significant differences in curvature, then problems can occur along their intersection curve.

Difficulties in tessellation lie in lack of attention to detail. Many special cases occur when dealing with very complex surface shapes and their intersection and trim curves. Many pathological numerical idiosyncrasies also occur when dealing with tens or hundreds of thousands of very small and possibly ill-conditioned triangles. Some of these conditions are outlined in Fadel and Kirschman (1995), Mandorli and Cugini (1995), and Otto et al. (1995a).

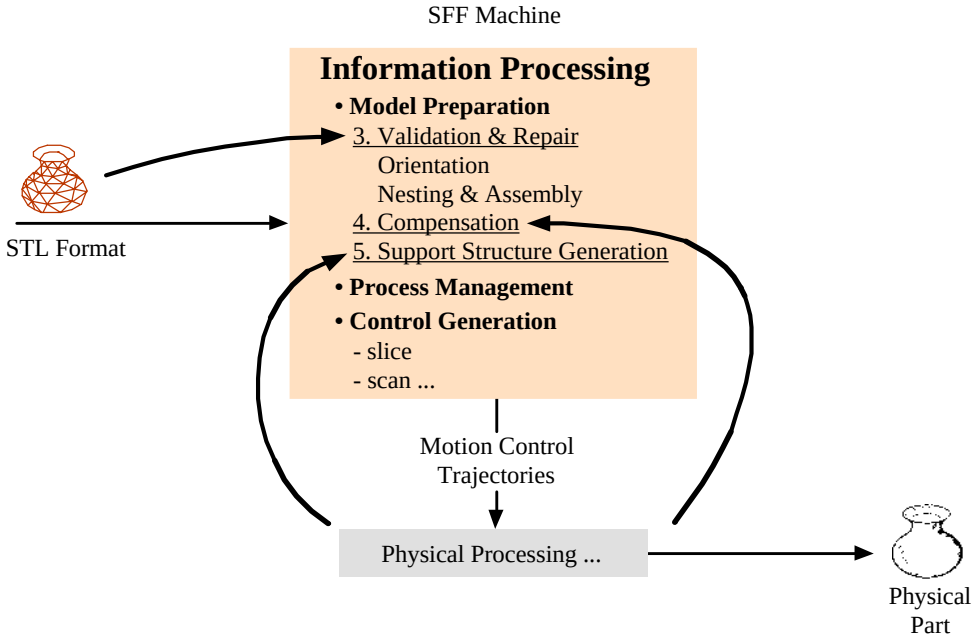


Fig. 8.5. Model preparation elements.

Fig. 8.6 illustrates how triangular facets are sometimes omitted by tessellating routines, creating gaps or holes in the resulting model. If Surface 1 is relatively flat, then it can be approximated fairly accurately with large triangles, defining a series of widely spaced points along the curve boundary with Surface 2. If, on the other hand, Surface 2 has high curvature, then it must be approximated by smaller triangles, thus defining a series of more closely spaced points along the common curve boundary with Surface 1. When each surface's set of distinct points along the common boundary are connected by straight lines to create triangles, gaps or missing facets will appear (shaded). This situation can be easily corrected, but it is typical of a whole multitude of anomalies that require detailed attention.

A hole in the boundary surface of a 3D model will cause the specific slice that intersects the hole to have an incomplete — not closed — contour boundary. This condition, in turn, generates an erroneous control signal to a laser beam or other solidifying agent, causing the agent to continue solidifying material until it reaches the wall of the material container, thus fabricating a thin ray of material emanating from the part and producing waste.

Anomalies sometimes occur because of the shortcomings of the STL data format. Although the format is simple, there is much redundancy in the data. The STL format defines each triangle independently, by its three vertices and its outward normal vector. But in any tessellation, every edge and vertex of adjacent triangles are coincident, as Fig. 8.6 shows. Since the file format does not account for this fact, numerical error can cause edges and vertices that are supposed to be coincident to have different values. Generally, one can preprocess an STL file and add topology adjacency information, *a posteriori*, by testing edges and vertices for sameness and adding pointers in the file. Again, numerical errors can creep in. Topology information is most reliably obtained during tessellation. Introducing topology information simplifies the slicing routines and speeds up execution (Rock 1991).

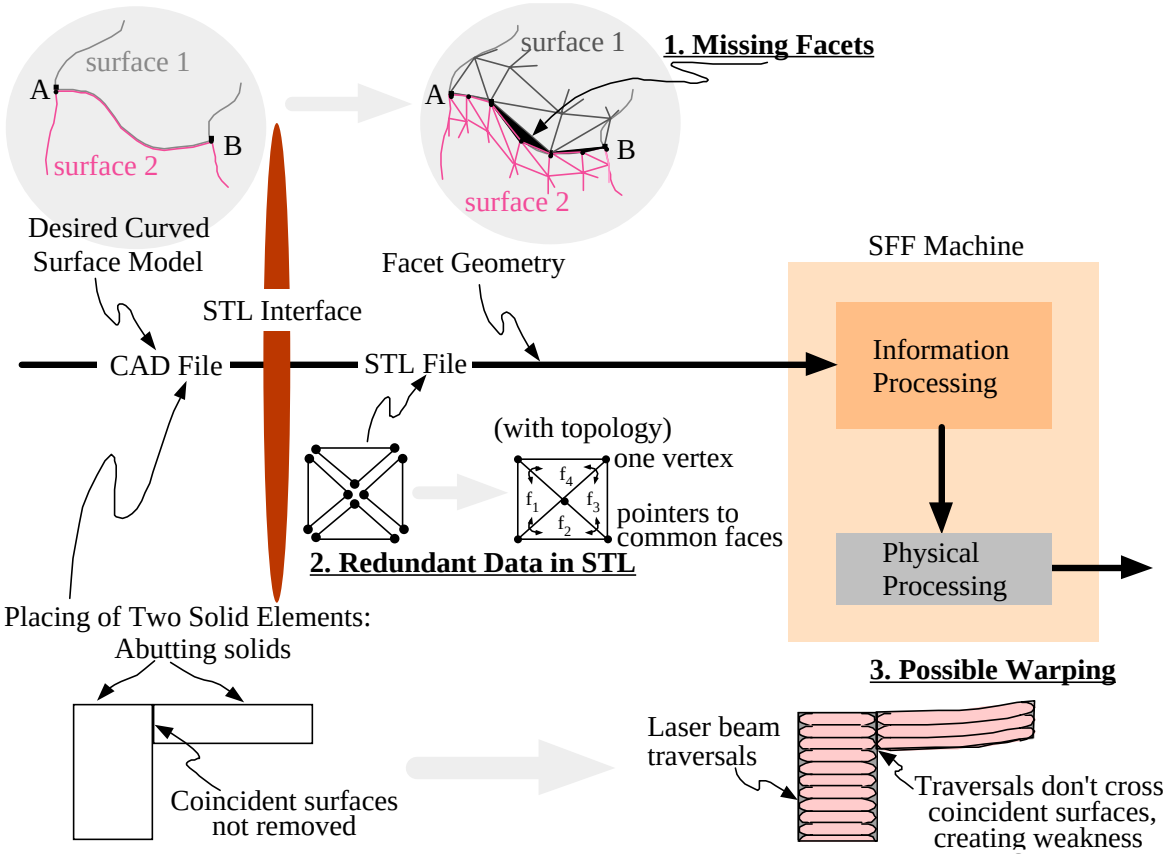


Fig. 8.6. Typical causes of error.

Finally, anomalies occur because designers do not always understand the physical processing implications of their choice of geometric elements, or their placement or manipulation. Solid models have sometimes been constructed by abutting two solids together, introducing coincident surfaces in the model, as shown in Fig. 8.6. In the CAD world, this is not a problem because the coincident surfaces have zero thickness. However, their presence changes the way the material is solidified, leading in some cases to internal stress buildup and ultimate distortion of the physical part.

Status of Model Repair

Various vendors have developed evaluation and repair software that determines if any triangles are missing in the tessellated model and fills the gaps with new triangles. Gaps consisting of a single missing triangle are easy to repair. The problem becomes more difficult when the gap consists of, say, 40 vertices. In this case, there are many different sets of triangles that could fill the hole. Unfortunately, the original sampled surface values needed to make that decision are not available. One option for creating the triangle-filling repair is to extrapolate the local surface curvature of known neighboring vertices. Ultimately, it is a matter of trade-offs. More complex solutions make sense only if high accuracy is achievable. It is much better to eliminate the problem up front. Various repair issues are discussed in Bohn (1993).

Table 8.4 lists the evaluation and repair capabilities of vendors visited by the JTEC/WTEC panel. D-MEC's system automatically repairs small cracks but requires manual repair of large cracks. CMET's STL file repair is topology-based. Presumably, CMET is checking for common vertices and edges, as discussed previously.

The Denken/Autostrade Solid Laser Plotter software displays damaged surfaces and has the capability for extensive slice manipulation.

Table 8.4
Status of Model Repair

COMPANY/ INSTITUTE	COMMENTS
D-MEC	Auto repair of small cracks, manual repair of large ones Auto thickness adjustment for 2½D models
CMET	STL file repair is topology-based
Denken/Autostrade (Solid Laser Plotter)	Displays damaged surfaces Extensive slice manipulation
Cubital	Solider Data Front End (DFE) Repairs STL files – cuts, patches, or trims facets, ...
Daimler Benz	CAD support tools generate error-free STL models

In Europe, Cubital representatives maintain that their Solider Data Front End (DFE) system has extensive model manipulation capability and can repair everything: it can cut, patch, or trim facets. Daimler Benz attacked the problem up front, which is possible for an internal system, by creating its own CAD support tools to generate error-free STL models.

Compensation

Since physical parts shrink and deform under processing, models are needed to anticipate and compensate for these shape changes. Most users today follow a trial-and-error procedure, iterating through several trial runs before achieving the desired part. The JTEC/WTEC panel saw a number of studies underway, summarized in Table 8.5, that are aimed at replacing this intuitive process with one founded on formal analytical tools. The underlying difficulty in developing analytical tools is lack of detailed process understanding.

Table 8.5
Status of Deformation Compensation

COMPANY/ INSTITUTE	COMMENTS
Tokyo University	Simulates stress buildup and deformation
Denken/Autostrade	Uses FEA to determine the optimal scanning strategies that minimize distortion (for specific geometries) Models laser-polymer interaction & resultant stress-formation
Kira	Compensates 1.5%-2% in z direction for effects of humidity (paper swelling)
IFAM (Bremen)	Optimizes designs for stress using genetic algorithms
IKP (Stuttgart)	Analyzes forces in multiple layers to gain better understanding of the resulting warp and curl

Research is underway at the University of Tokyo to simulate stress buildup and the resulting deformation. Denken Engineering/Autostrade is considering using finite element analysis (FEA) to create optimal scanning strategies that minimize distortion for specific geometries. This work requires the modeling of laser-polymer

interactions to determine the resultant stress formation. Kira simply compensates 1.5-2% in the z direction to account for the swelling of its paper due to humidity. Nakamura Pattern Making Company considers high quality and precision to be the most important requirements, even more important than price. In fact, Nakamura bought a more expensive SFF machine rather than risk compromising these requirements with a less expensive machine.

Projects dealing with part distortion are underway in Europe as well. At the Fraunhofer Institute for Applied Materials Research (IFAM), designs are being optimized for stress using genetic algorithms, and the Institute for Polymer Testing and Polymer Science (IKP) at the University of Stuttgart is using finite element techniques to predict forces in multiple layers to better understand the resulting warp and curl.

Support Structures

Table 8.6 summarizes the current work that the JTEC/WTEC panel observed on development of support structures. The panel found that in Japan much of the software activity for generating support structures for RP parts is internal and proprietary. For example, CMET's customers design supports manually. While engineers at CMET are aware of existing automatic support-generator software that may suffice (see next section), they have decided to develop their own.

Concerning European activity for support structures, panelists saw very efficient capabilities under development. The scientists at EOS are working on optimizing the amount of material used (mesh style supports) in their Skin and Core Support software. MAGICS software from Materialise allows the building of lattice-like support structures that constitute only 10% of the part's resin volume and build time. Panel members understand that Laser 3D has some capability in designing support structures, but have no details. IKP is developing new hatching strategies for both sintering and stereolithography processes.

Table 8.6
Status of Support Structure Development

COMPANY/ INSTITUTE	COMMENTS
CMET (Japan)	Customers design supports manually Internal version generates supports automatically
Materialise N.V. (Belgium)	Lattice-like support structures require only 10% of resin volume and build time
EOS (Germany)	A mesh-style support is generated by Skin and Core Support software
Laser 3D (France)	Has a capability
IKP (Stuttgart)	Has new sintering and stereolithography hatching strategies

RP Software

Several independent software houses have emerged in Europe over the past few years to support the growing RP market. The software activity in Japan seems to be in the service bureaus, like the medical software being developed by INCS, although the Ricoh SolidDesign™ solid modeler is an excellent starting point for developing an RP capability. The United States has many small RP software houses that cover all aspects of the market. Some software companies have extended their CAD and model creation capabilities, like Imageware in the United States. Others provide software for RP-specific operations like STL data viewing, data transfer, data models, or support generation, with the goal of independence from vendors. Materialise in Europe and Brock Rooney and Associates (1992) in the United States are typical of this latter category. The establishment of newer RP software companies, such as DeskArtes in Finland (http://www.deskartes.

fi/rt.html), indicates that the market in Europe will continue its rapid growth. See Wohlers at http://lamar.colostate.edu/~wohlers/ for market data.

Research institutes such as BIBA (http://www.biba.uni-bremen.de/groups/rp/rp_page.html) have also developed a variety of interfaces, from a VDA-to-STL translator to new software that combines the point clouds from a multiviewed scanned object into a contoured model in the CLI layer format.

Software offerings of Materialise are representative of the excellent functionality available in Europe (http://www.materialise.com/). Materialise offers three major RP packages, whose specific capabilities are shown in Tables 8.7 and 8.8 and Fig. 8.7:

- MAGICS (visualization, measurement, manipulation, and support generation for STL files)
- Contour Tools (detects, visualizes and repairs defective contours; performs slicing, repair of bad STL files, and support-generation based on contours)
- CT-Modeler System (handles CT scan data for RP & CAD)

Table 8.7
MAGICS Software from Materialise

Level*	Features
1. MAGICS QM (Quotation Maker)	Visualization of STL files View modes: wireframe, shading, triangle view, ... Visual detection of bad STL files Generation of 2D sections along x, y, and z axes Measuring in 2D and 3D Basic manipulations: rotate, mirror, rescale Build time estimation
2. MAGICS RP (Rapid Prototyping)	Advanced part manipulation: pick/place (workspace) and bottom plane (orientation) Text utility to label STL files Build time calculation optimizes machine productivity Cutting of STL files, including non-straight cutting profiles Punching holes into STL files to overcome trapped volumes
3. MAGICS SG (Support Generation)	Automatic and interactive support generation Different editing levels to customize supports Perforated supports, allowing • less resin consumption • faster building • easy removal • better draining Part and support visualization in 3D Fast direct slicing of supports with optimal scan pattern

* The full set of Level 2 features includes those of the previous level, namely, Level 1; the full set of Level 3 features includes those of the previous levels, namely, Level 2 and Level 1.

The CT-Modeler package provides a complete interface from a CT medical scanner to CAD systems or RP machines, as shown in Fig. 8.7. MIMICS is the medical front end of the package, in which segmentation of structures is done using 3D selection and editing tools. A 3D color image is generated from slice data. C-SUP generates support structures. Perforated support structures build four times faster, consume much less material, and are easier to clean than conventional supports. CTM interpolates slice data across layers and

interfaces directly to RP machines. It can handle high-order interpolation algorithms. MedCAD takes the medical scan data and creates surface files that are directly usable for the design of custom prostheses in CAD systems. It supports an IGES interface.

Table 8.8
Contour Tools Software from Materialise

Level	Features
1. Interactive Slicer (C-STL)	Defective contours seen in red Editing to correct contours on single or multiple layers Add/Delete contours (overcome trapped volumes) Compensate for overshoot in z-direction on SLI & CLI files (also create hollow parts)
2. Contour-based Support Generator (C-SUP)	Generate support structures based on contour files Generate perforated supports that drain "quickly and perfectly" and optimize support material Visualization in 3D
3. Contour Tools input & output formats	SLC & SLI (3D Systems) CLI (EOS) SLC (Stratasys) F&S (Fockele & Schwarze) BIN (Sanders)

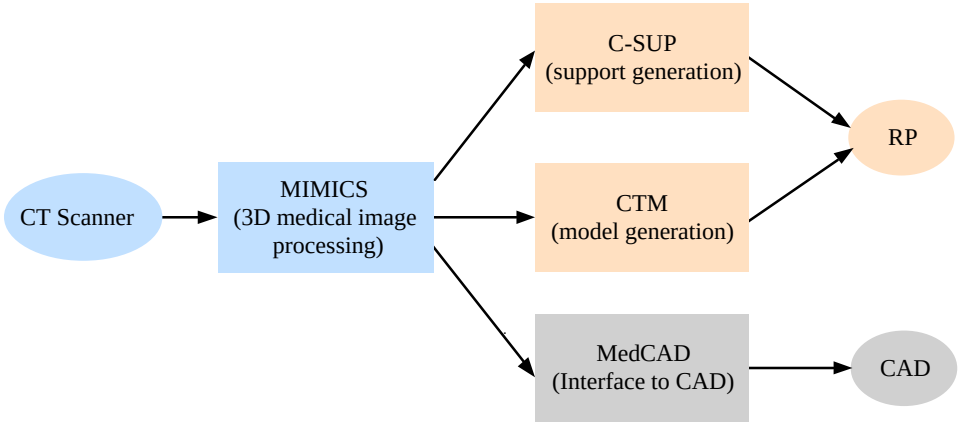


Fig. 8.7. CT-Modeler functions.

SYSTEM SIMULATION

Several software projects are underway, primarily in Germany, to simulate the capabilities of various SFF machines for the purpose of giving users a means of determining which particular rapid prototyping machine (or process) is preferable for a given set of requirements. On the one hand, such projects seem premature, because SFF processes are not well understood, existing process models are incomplete, and new processes and machines continue to be announced. On the other hand, this project can serve as a mechanism for codifying existing RP knowledge and may identify areas for additional research. More importantly, it may also help new users be productive sooner, thereby making SFF more accessible to a broader community.

A VR simulation package is being developed at the University of Stuttgart that will provide feedback to the user on the impact of modifications by showing the effect of changing geometry, processes, and so forth. Results will include material buildup and associated stresses, dimensional errors, and material strengths. This is a very ambitious project.

The simulation software under development at the IKP in Stuttgart accepts input data such as part material, surface finish, and desired strength, among other specifications, and selects the RP process required to fabricate the tools, as well as the processing sequence needed to produce the part.
These projects recall an interesting Japanese perspective on codification of information, which the panel gleaned during its visit to the IMS Promotion Center in Tokyo (see also Sites, 1996, 60-68), namely, Yoshikawa's categorization of the evolution of technical knowledge.

The categorization, shown in Fig. 8.8, starts with the creation of fundamental knowledge through the basic and applied research stages, which is public domain knowledge. The innovation or new technology stage uses this fundamental knowledge to generate proprietary knowledge for commercial purposes — including development and manufacture. When islands of this developed technological knowledge achieve widespread use and are thoroughly understood and public, then the knowledge is codified or systematized to reveal missing elements that, in turn, can lead to new basic research. Codification also ensures that this knowledge is not ultimately lost, especially when it lies at interfaces between disciplines.

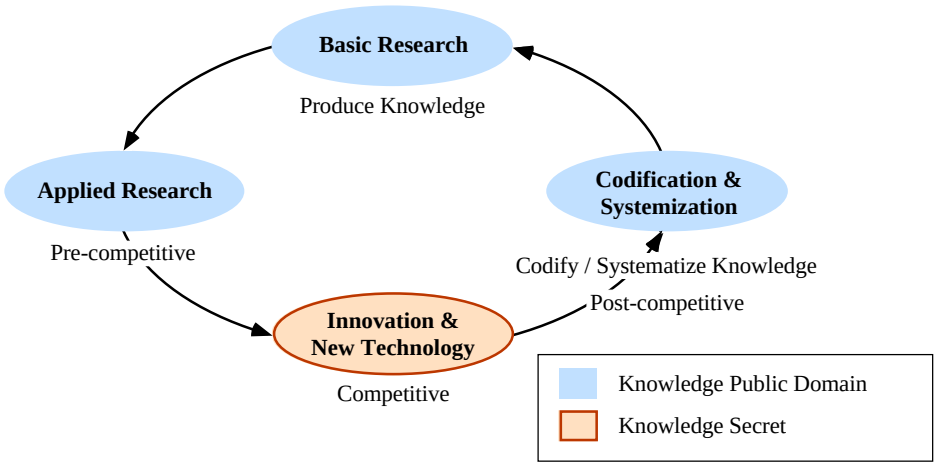


Fig. 8.8. Yoshikawa's categorization of the evolution of technical knowledge.

One modification to this view may be offered: knowledge is not generally created in one large batch process, but perhaps in a more fractal manner, traversing the cycle in many small chunks.

CONCLUSIONS

In Japan, the JTEC/WTEC panel was told that solids creation is the major stumbling block to increased use of RP. At the same time, the panel was made aware of an awakening realization in Japan that solid modeling is useful and needs to be pursued more vigorously. This is expected to happen rapidly, led by large companies.

There is an unwavering drive in Japan in both the user and vendor communities to produce the highest-quality parts possible. The users want more precision from their machines. This is one reason why there is so much development of proprietary software.

In Japan, the interest in standards for data exchange comes primarily from academia and research organizations. Standardization will not occur until the larger companies get involved. MITI appears more intent on fostering the development of machines and consolidating the industry than on promoting standardization efforts.

In the United States, there is much interest in standardization, and some limited activity, but the efforts have not coalesced. They may be stimulated by some recent National Science Foundation program announcements for research in neutral or intermediate representations for RP part geometry. Standardization will become even more important in the future as SFF machines start dealing with multiple materials.

Europe is heavily committed to RP, with concentrated efforts on building new machines and businesses, as well as on establishing a strong research base. There are more new software companies and more software research projects in Europe than in Japan; the United States continues to lead. As in Japan, there seems to be more national cooperation among research projects and companies in Europe than in the United States. These national programs could offset the current market advantage held by the United States, because the U.S. RP industry consists primarily of small companies that are at a vulnerable stage.

REFERENCES

3D Systems, Inc. 1988. Stereolithography Interface Specification.

3D Systems, Inc. 1994. SLC File Specification.

Aubin, Richard F., 1994. A world wide assessment of rapid prototyping technologies. In *Proc., Solid Freeform Fabrication Symposium.* Austin, TX.

Beascoechea, A., and M. J. Wozny. 1995. On three-dimensional heuristic packing. In *Proc., Solid Freeform Fabrication Symposium*. Austin, TX.

Beascoechea-Gangoiti, A. 1996. *3D packing for solid freeform fabrication: A heuristic approach.* PhD thesis. Rensselaer Polytechnic Institute, Troy, NY.

Bohn, J. 1993. *Automatic CAD-model repair: Shell closure.* PhD thesis. Rensselaer Polytechnic Institute, Troy, NY.

BRITE/EuRAM. 1994. *Common Layer Interface (CLI)*, Version 1.31. BRITE/EuRAM Project BE5278, Rapid Prototyping Techniques.

Brock Rooney & Associates, Inc. 1992. "STH file format file description, version 1.2." Birmingham, MI.

Cubital, Ltd. N.d. Cubital facet list (CFL) guide. In *Solider 5600 system DFE workstation users guide.*

Dolenc, A., and I. Mäkelä. 1992. LEAF: A data exchange format for LMT processes. In *Proc., 3rd Intl. Conf. on Rapid Prototyping*. Dayton, OH.

_____. 1994. Slicing procedures for layered manufacturing techniques. *CAD* 26(2).

_____. 1995. Rapid prototyping from a computer scientist's point-of-view. Working paper, Internet conf. on rapid product development. http://www.mcb.co.uk/services/conferen/dec95/rapidpd/stutt/stutt.html.

Fadel, G. M., and C. Kirschman. 1995. Accuracy issues in CAD to RP translations. Working paper, Internet conf. on rapid product devt. http://www.mcb.co.uk/services/conferen/dec95/rapidpd/fadel/fadel.html.

Fockele, M., and D. Schwarze. 1994. New methods and dimensions in rapid prototyping. In *Proc., 27th Intl. Symposium on Automotive Technology and Automation* (27th ISATA).

Frank, D., and G. M. Fadel. 1994. Preferred direction of build for rapid prototyping processes. In *Proc., 5th Intl. Conf. on Rapid Prototyping*. Dayton, OH.

Ganesan, K., and G. M. Fadel. 1994. Hollowing rapid prototyping parts using offsetting techniques. In *Proc., 5th Intl. Conf. on Rapid Prototyping*. Dayton, OH.

Gilman, C. R., and S. J. Rock. 1995. The use of STEP to integrate design and solid freeform fabrication. In *Proc., Solid Freeform Fabrication Symposium.* Austin, TX.

IMS Test Case #6 Coordinating Partners, and IPA, Stuttgart. 1994 (January). *Proc., Intl. Conf. on Rapid Product Development*. Stuttgart, Germany.

IMS Test Case #6 Coordinating Partners. 1994 (June). Final Report, Test Case #6. Submitted to the International IMS Committee.

Jamieson, R., and H. Hacker. 1995. Direct slicing of CAD models for rapid prototyping. *Rapid Prototyping Journal* 1(2).

_____. 1995. Direct slicing of CAD models for rapid prototyping. Working paper, Internet conference on rapid product development. http://www.mcb.co.uk/services/conferen/dec95/rapidpd/jamieson/jamieson.html.

Mandorli, F., and U. Cugini. 1995. Identification of process relevant form structures for stereolithography within solid models. In Proc., IFIP WG5.3, Life cycle modelling for innovative products and processes. PROLAMAT'95. Berlin.

Otto, H. E., F. Mandorli, F. Kimura, and U. Cugini. 1995a. Handling of process relevant form structures within solid freeform fabrication using a feature-based approach. In Proc., 2nd Intl. Conf. on Precision Engineering, ICMT '95. Singapore.

_____. 1995b. Extension of feature-based CAD systems using TAE [typed attribute entity] structures to support integrated rapid prototyping. In *Proc., ASME Computers in Engineering Conference and the Engineering Database Symposium (CE95).* Boston.

Rock, S. J. 1991. *Solid freeform fabrication and CAD system interfacing.* MS thesis. Rensselaer Polytechnic Institute, Troy, NY.

Rock, S. and M. J. Wozny. 1991. A flexible and extendible SFF format. In *Proc. Solid Freeform Fabrication Symposium*. Austin, TX.

Sachs, E., S. Allen, M. Cima, E. Wylonis, and H. Guo. 1995. Production of injection molding tooling with conformal cooling channels using the three dimensional printing process. In *Proc. Solid Freeform Fabrication Symposium.* Austin, TX.

Sites. 1996. This reference designates the companion volume to this JTEC/WTEC report: Prinz, F. B., ed. *JTEC/WTEC panel report on rapid prototyping in Europe and Japan.* Vol. II. *Site reports.* Baltimore, MD: Loyola College. NTIS Report #PB96-199583.1

Suh, Y. S., and M. Wozny. 1994. Adaptive slicing of solid freeform fabrication processes. In *Proc., Solid Freeform Fabrication Symposium*. Austin, TX.

Thompson, D. C., and R. H. Crawford. 1995. Optimizing part quality with orientation. In *Proc., Solid Freeform Fabrication Symposium.* Austin, TX.

Turner, J., J. Pegna, and M. Wozny, eds. 1991. *Product modeling for computer-aided design and manufacturing.* Amsterdam: North-Holland.

Verband der Automobilindustrie. 1987 (January). VDA Surface Interface, Ver. 2.0. Westendstrasse 61, D-6000 Frankfurt am Main, Germany.

Vuyyuru, P., C. Kirschman, G. M. Fadel, A. Bagchi, and C. Jara-Almonte. 1994. A NURBS based approach for rapid prototyping realization. In *Proc., 5th Intl. Conf. Rapid Prototyping.* Dayton, OH.

Weiler, K. J. 1986. *Topological structures for geometric modeling.* PhD thesis. Rensselaer Polytechnic Institute, Troy, NY.

Wilson, P., M. Wozny, and M. Pratt, eds. 1992. *Geometric modeling for product realization.* Amsterdam: North-Holland.

Wozny, M., J. Turner, and K. Preiss, eds. 1990. *Geometric modeling for product realization.* Amsterdam: North-Holland.

Wozny, M., H. McLaughlin, and J. Encarnacao, eds. 1988. *Geometric modeling for CAD applications.* Amsterdam: North-Holland.

CHAPTER 9

RAPID PROTOTYPING MACHINE DESIGN

Emanuel Sachs

INTRODUCTION

In order to make sense of the wide array of rapid prototyping (RP) machine designs in existence today, it is helpful to examine them in terms of a classification scheme encompassing a number of subgroups. In the following discussion, an attempt is made, wherever possible, to identify the essential technical challenges faced by subclasses of machines and to examine a representative set of solutions to these challenges. Some groupings of machines are examined that cut across the boundaries established in the classification scheme proposed here.

MOTIVATION FOR MACHINE DESIGN

The motivation for and the role of RP machine design seems to be viewed somewhat differently in different regions. In the United States and in Europe, RP is looked at as having high impact on the product development process, shortening development cycle times, and getting better products to market. That is very high leverage, and that is why there is a good deal of interest in RP. While these advantages are acknowledged in Japan, RP must compete there with CNC machining, which the Japanese know very well and have done very successfully. The Japanese observe that in the long run the important question is who supplies the best equipment. Their strategy of focusing on this goal has served the Japanese well in the machine tool and other markets. As a result, the Japanese have a clear strategy to develop machines that are the best in the world, at the lowest cost, and with the highest accuracy.

CLASSIFICATION SCHEME

A number of experts have proposed RP classification schemes that are based on the physics of the processes. For the purposes of this chapter, a classification scheme is presented that is based on the operation of the machines themselves. The classification is done as a matrix, as shown in Fig. 9.1. The two axes of the matrix are Imaging Strategy and Imaging Mechanism.

Imaging Strategy

Imaging strategy, the horizontal axis of Fig. 9.1, is the approach used to define the image of a single layer and has direct analogy to the methods used to create images in graphics printing. One approach is to use a raster, where the image is created as a series of contiguous or overlapping straight line segments. This is the method

used to create TV images and is the predominant method for printing graphics (desktop computer printers all work with a raster strategy).

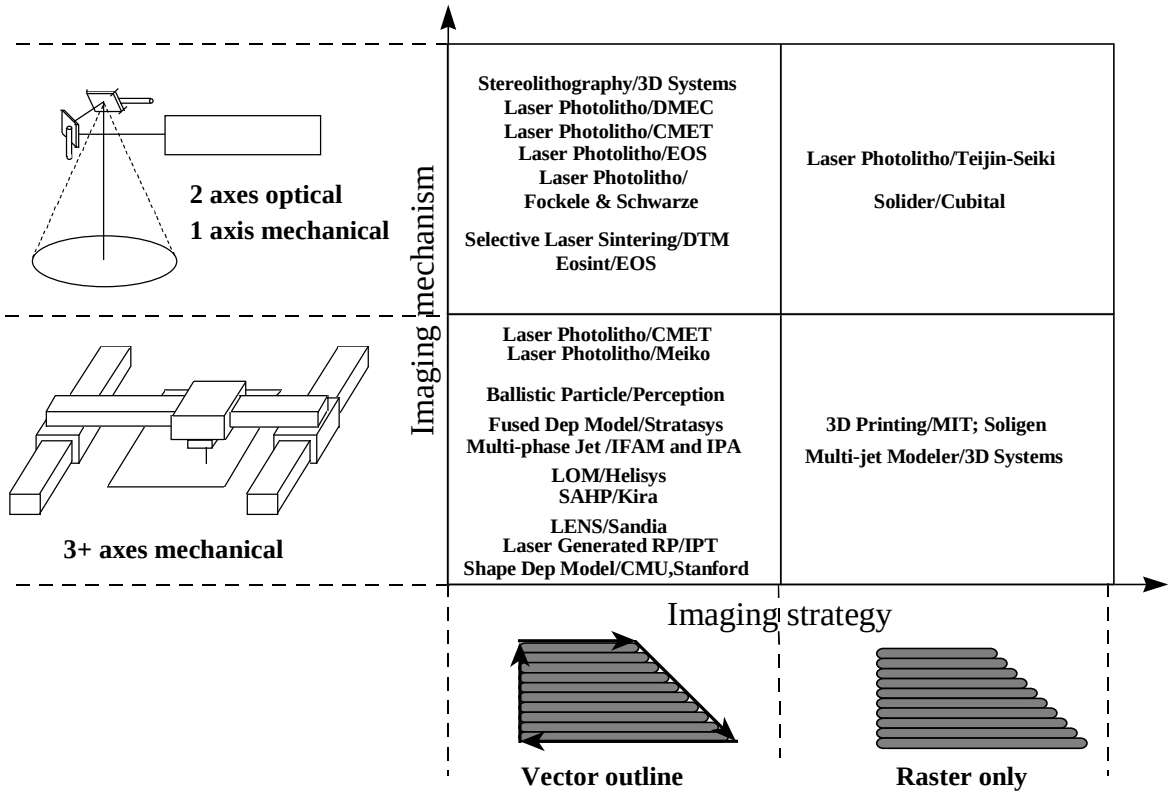


Fig. 9.1. Matrix classification scheme for RP machines.

The alternative method is to draw at least the outline of the image with vector motions, as illustrated by the arrows in Fig. 9.2. The interior could be filled with a vector motion or, more commonly, with a raster fill pattern, also as illustrated in Fig. 9.2. Flatbed pen plotters employ vector motions to draw images. The fundamental trade-off here is between speed and precision. A raster approach is faster, since no changes in direction are required and it can often be done in parallel (with a line of pens, figuratively speaking). However, a raster pattern produces only an approximation of the outline of the part, with discretization errors apparent on any edge that is not parallel to the raster motion. Such "aliasing" is evident in Fig. 9.2. This situation is avoided by the vector approach.

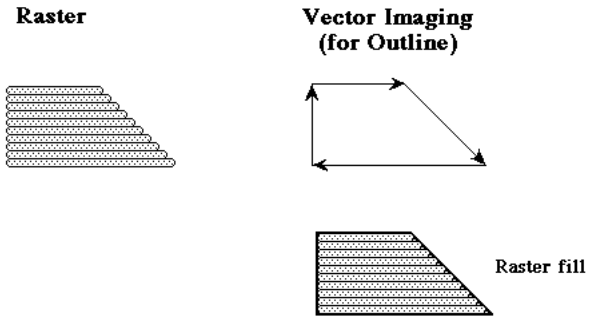


Fig. 9.2. Two approaches to the strategy for imaging a layer.

Imaging Mechanism

Imaging mechanism, the vertical axis of Fig. 9.1, is a classification of the mechanism used to define the 3D geometry of the part. In one case, all three axes are defined by mechanical motion. For example, a 2D mechanical motion using an x-y gantry system is used to define the geometry of each layer, and the third axis is effected by dropping the piston down vertically. In the alternative case, each 2D slice image is defined optically, and the third axis is due to a mechanical motion. The most common optical imaging technique is the use of galvanometer mirrors. One might argue that galvo mirrors are mechanical devices as well; however, they have a distinct set of performance issues associated with them, and their use dictates a fundamentally different machine design as compared to mechanical slides.

The matrix of Fig. 9.1 shows representative types of equipment from most of the RP machine vendors and research groups known at the time of this JTEC/WTEC study. Note that the machines divide roughly evenly between two axes optical and all axes mechanical. However, use of vector outline predominates over raster only (this is in sharp contrast to desktop computer printers, where raster dominates).

GROUP 1: LASER/MIRROR

The most important class of machines being developed in Europe and Japan are machines that scan a laser using galvo mirrors. Both vector-outline and raster-only types exist within this class, as shown in Fig. 9.3.

In the very simplest case, this type of machine consists of a laser, a focusing lens, and two axes of galvo mirrors, as illustrated in Fig. 9.4. Examination of some of the critical elements of this system and some of the issues that lead to more complexity in this system provides some insight into the equipment being built today.

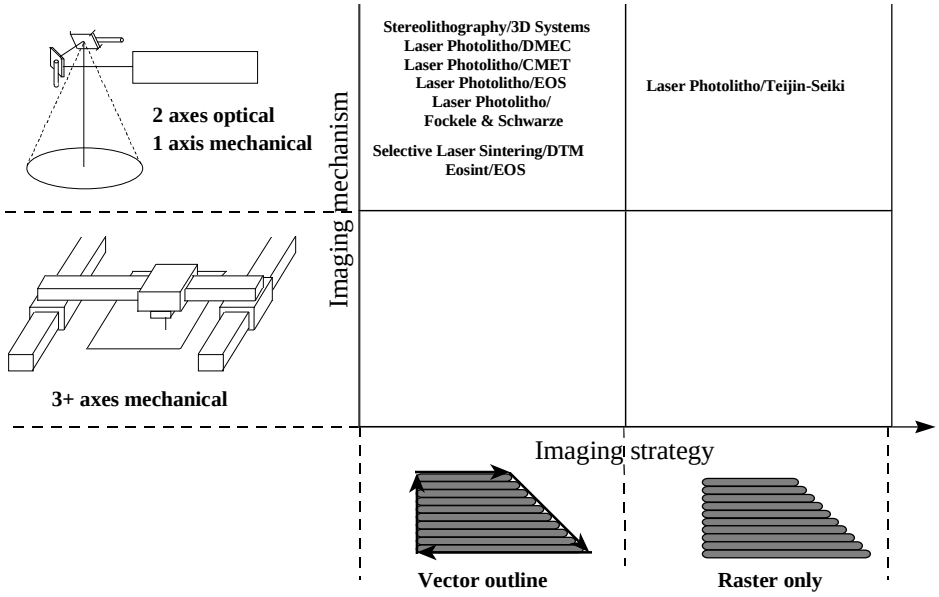


Fig. 9.3. Machines that use lasers and optical imaging.

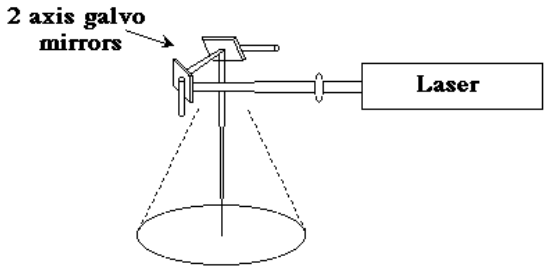


Fig. 9.4. The simplest configuration of a laser mirror system.

Scanning Galvo Mirrors

The performance of the scanning galvo mirrors is a factor that limits the performance of the system, as the galvos mandate a trade-off between speed and accuracy in the imaging of a layer. Since this machine element can be partly responsible for the competitive positioning of RP equipment, a crucial question is whether to make the galvos or to buy them. Both decisions are represented in the market. 3D Systems exemplifies both decisions. For the SLA-250 the company started by buying General Scanning mirrors. When it went to the SLA-500, it decided to build its own mirrors because it couldn't get the desired performance in off-the-shelf mirrors. 3D Systems continued to build custom scanners for the SLA-350. Teijin Seiki builds its own scanners in its own plant (the plant is not dedicated to scanners but has a significant effort in building scanners). EOS builds its own scanners. DTM uses General Scanning scanners. This company has ridden the curve of improvement as General Scanning has improved its products — at least partly in response to the requirements of RP vendors.

The general trend is that the increased accuracy of materials (especially photopolymers) has driven machine designers to improve the accuracy of the mirror scanners. They have responded either by working with an established vendor such as General Scanning or by building their own scanners. When they build their own scanners, they also build their own control electronics, which are often based on digital signal processing.

Table 9.1 shows the stated accuracies for a number of galvo systems at specified scanning speeds. This data is derived from a combination of published specifications and conversations. It is important to note that it is very easy to confuse accuracy (proximity to target) and precision (repeatability) in conversation and probably in specifications as well. It is also easy to confuse static and dynamic accuracy. Thus, some uncertainty must be acknowledged concerning the numbers presented in Table 9.1; nonetheless, the consistency of the data from different vendors lends credence to the numbers. The Teijin Seiki machine is a raster-only machine, and the higher accuracy specification can be understood by recognizing that such a machine does not have to execute coordinated motions of two axes.

Table 9.1
Mirror Scanners: Accuracy Specs

Machine	Scan Speed	Accuracy
3D Systems SLA500, 350	5 m/s	±50 microns
CMET all mirror machines	5 m/s	±50 microns
Teijin Seiki all machines	15 m/s	±12.5 microns
EOS Stereos	2 m/s	±50 microns
DTM Sinterstation 2000	2 m/s	±50 microns
EOS Eosint S 700*	2.5 m/s	±100 microns

* This machine has two lasers and two scanners — the two lasers operate together to either build one larger part or multiple smaller parts.

The accuracy of the final part is dependent on both the equipment and the materials. With recent improvements in equipment, the predominant limitation lies with the distortions introduced by the materials systems. This is especially true of processes such as selective laser sintering where there are significant distortions, but it is true of stereolithography as well. Hopefully, future improvements in materials systems will demand that the equipment builders revisit their equipment designs and improve them again, as they have in the past.

Accurate calibration of laser scanner systems is key to delivering the improved systems performances achieved today. If a scanner system has an accuracy of 50 microns over a range of 500 mm, the accuracy is 1 part in 10,000. Such accuracies can only be achieved by calibration of the fully assembled machine. Several methods are in use, all resulting in a calibration table that is captured electronically and used by the machine. 3D Systems puts down a plate with precision-drilled holes. Operators shine a laser through the holes, collect the light, and image it onto a photodetector. The machine is then used to maximize the light transmission, and designers then know the machine settings that correspond to the hole positions. DTM burns holes in a mylar film and then inspects that off-line. EOS exposes photosensitive paper and inspects that off-line.

Consistent Spot Size

Laser/galvo systems pivot the laser beam in order to scan it over the working field. In the most typical system, a lens is placed before the mirrors, as shown in Fig. 9.5. The result is that the beam will be in focus at only one distance along the optical path from this lens. As the beam is scanned over the surface of the working area from the center position, its optical path increases; hence, the laser cannot be in focus at all locations. The effect is more pronounced the closer the mirrors are to the imaging plane, for a given size of the imaging surface, due to the larger angles of deflection of the mirrors.

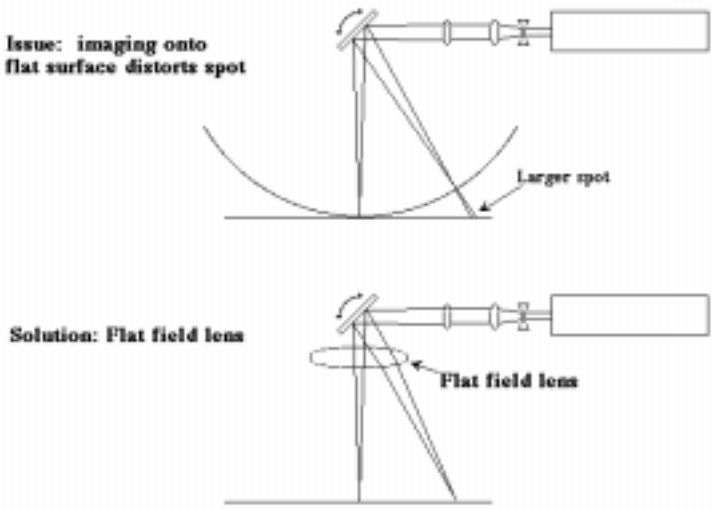


Fig. 9.5. The spot size changes across the vat in a galvo system (top) unless flat field optics are used (bottom).

There are several solutions to this problem. In some systems, the distortion is tolerated. Especially in systems with a large focal spot size, the increase in spot size caused by movement of the beam to the edges is considered to be a tolerable effect. In some equipment, the optical path length is intentionally increased by using a focusing lens with a long focal length. Examples include the SLA 500 and the SLA 350 from 3D Systems, which have a mirror at the top of the machine and which double the optical path back to scanners housed below. The result of this approach is to effectively move the scanners further away from the imaging plane, resulting in lower angles of deflection. Thus, the change in optical path from the center of the field to

the edge of the field is a much smaller fraction of the optical path, and the effect on the laser spot size is similarly reduced. This approach has the added benefit of providing a beam that is closer to perpendicular when it is incident on the vat surface, resulting in less distortion of the circular spot.

An alternative solution is to fundamentally modify the optical path by using a flat field lens that is placed after the mirror system. Such a lens system has a different focal length, depending on the position at which the laser hits the lens. The flat field lens is thus able to maintain a constant focal spot size at the image plane. This type of optical element is more costly, however. The JTEC/WTEC panel is aware of only two companies that use this approach: CMET and EOS.

Starting and Stopping

In terms of drawing the scan vector, the optimum situation is one in which the vector drawn by a laser/galvo system is uniform along its length and has the same width near the beginning, middle, and end. If the laser is turned on to full power and the mirrors are simultaneously accelerated, the effect will tend to be like that shown in Fig. 9.6, where the vector is wider near the ends where the laser spot is either accelerating or decelerating and the power density of the laser is higher.

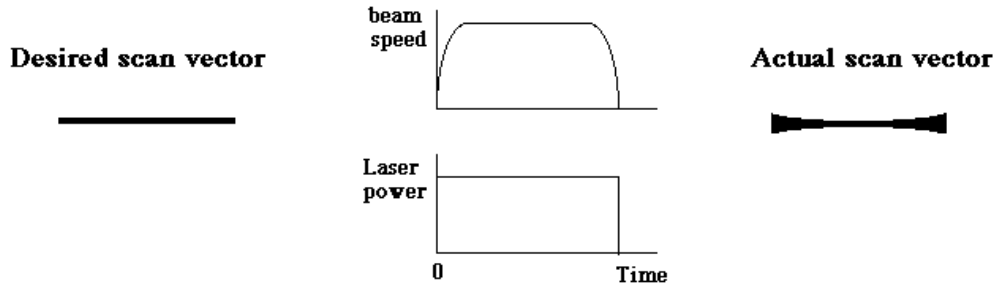


Fig. 9.6. Turning the laser full on immediately results in a scan vector that is wider at the beginning and end of the vector.

A number of solutions to this problem are currently in use. Teijin Seiki uses an acousto-optic modulator (AOM), which is placed between the laser and the galvo system. With this device, it is possible to do pulse-width modulation of the laser power that goes through the galvos; by varying the duty cycle of the laser power reaching the vat, engineers are able to effectively reduce the laser power during acceleration and deceleration of the beam, resulting in a constant power density at the vat. D-MEC uses a "high-speed light modulator" (probably this is an AOM). In its equipment, DTM does pulse-width modulation of an RF-excited laser.

3D Systems uses an AOM, but only for turning the laser on and off at the beginning and end of the vector, not for pulse-width modulation. As noted earlier, 3D Systems builds its own scanners and control electronics, and these high-speed systems allow the company to minimize the impact of the acceleration and deceleration phases of its vectors.

GROUP 2: LASER

Returning to the classification scheme, machines that use lasers constitute a broad class of systems that cut across categories of the matrix presented here. (The laser/galvo systems make up a subgroup of these systems.) This class is shown in Fig. 9.7.

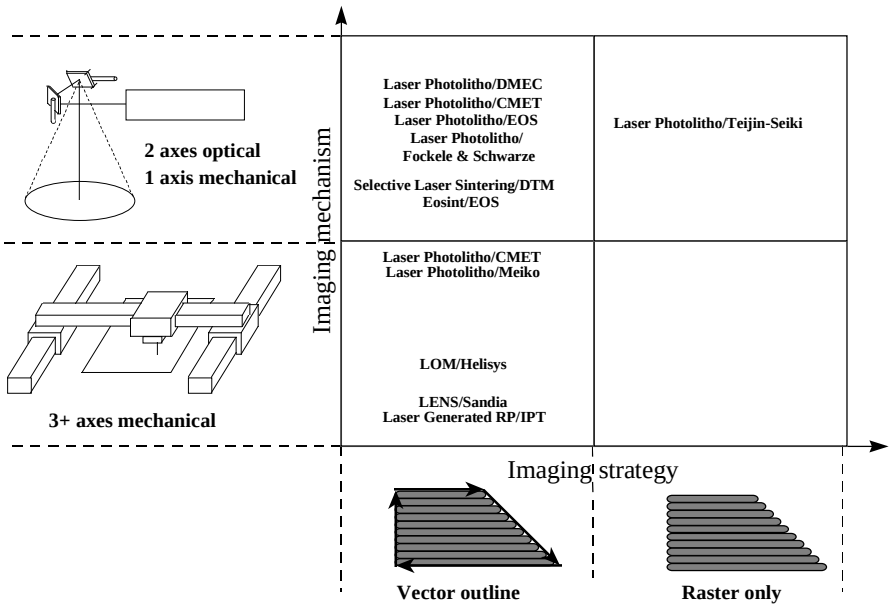


Fig. 9.7. Systems with lasers.

Spot Size

Table 9.2 shows the spot size achieved in various laser-based RP machines, including both mirror and gantry types of machines. As can be seen, most systems have spot sizes of 150-200 or 250 microns. There are a few exceptions, notably the DTM machine that has a significantly larger spot size (400 µm), and two machines with significantly smaller spot sizes: a 3D Systems Beta machine (80 µm) and the Nagoya photomolding machine (5 µm).

Table 9.2
Spot Size

Machine	Spot size (diameter)
3D Systems SLA 250, 350, 500	250 microns
3D Systems Beta	80 microns
DMEC (500 x 500 mm)*	150 microns
DMEC (800 x 1000 mm)	300 microns
CMET mirror	200 microns
CMET gantry**	130 microns
Teijin Seiki	150 microns
EOS Stereos	200 microns
DTM	400 microns
Sintering/Bavarian Laser Center	Concentric dual beam
Helisys/LOM	250 microns
Photomolding/Nagoya	5 microns

* older, smaller machine has variable spot size
** variable spot size, 130-1500 microns

An important source of perspective on the data of Table 9.2 is to recognize that there is a fundamental lower limit to the spot size that can be achieved from a collimated light source. This is given by the expression

$$\text{Minimum spot size} = \frac{\lambda \cdot f}{d}$$

where λ is the wavelength of the light, f is the focal length of the focusing lens, and d is the diameter of the collimated beam that enters the lens. Thus, the smallest focal spot will be achieved with a large-diameter beam entering a lens with a short focal length.

As noted above, in a laser/galvo system, there is an advantage to moving the mirrors (and therefore focusing lens) far from the imaging plane in order to achieve better control over the size and shape of the focal spot. However, as can be seen from the equation above, a longer focal length acts to increase the minimum spot size that can be achieved. In order to compensate for this effect, a beam expander may be placed in the optical path before the focusing lens. This solution is employed in many laser/galvo systems, as shown in Fig. 9.8.

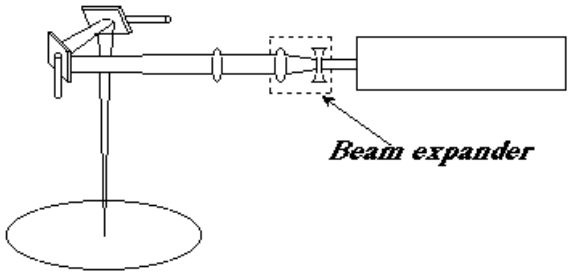


Fig. 9.8. A laser/mirror system with a beam expander in the optical path.

This strategy, too, has its limits. As the beam diameter is increased, the mirrors in the galvo system must be increased in size and mass, potentially resulting in a loss of performance. However, most laser/galvo systems do use a beam expander in order to bring the focal spot down into the typical range of 150-200 microns.

The larger, 400-micron spot size of the DTM machine can be understood by noting that no beam expander is used in this machine. The laser sintering machine at the Bavarian Laser Center uses a concentric dual beam. The larger beam preheats and anneals the powder, while the inner beam performs the sintering.

A standout on the smaller end of the scale is the small, 80 µm spot size of the 3D Systems Beta machine, which is a retrofitted SL250 machine in beta testing. In this machine, several modes of the HeCd laser are filtered out, resulting in a beam that can be focused to a smaller spot size. In the process, most of the beta energy is lost.

Achieving a small and well-controlled spot size is less difficult in a gantry machine. For example, in the LOM (laminated object manufacturing) machine, the focusing lens is carried on the gantry and is much closer to the imaging plane (approximately 10-15 cm distance) than it is in a galvo mirror machine. For this reason, no beam expander is needed before the focusing lens. Further, there is no change in angle of incidence of the beam, and hence no distortion of the shape of the beam. The photomolding machine at Nagoya is intended for MEMS (microelectromechanical) application and so uses a very small spot indeed. The gantry construction of this machine helps in achieving this small spot size.

A possible strategy with a laser machine is to change the size of the spot, depending on the geometry being imaged. For example, a small spot size might be used to scan the perimeter of a part in a vector motion with fine detail, followed by use of a large spot to achieve a raster fill of the geometry. An older DMEC machine and a CMET machine have such capability.

Recoating in Laser Photolithography

Many machines in the laser class are photolithography machines (both vector and gantry), and recoating is an important aspect of the design and performance of these machines. The technique used can influence (1) the range of resin properties that are allowed in a machine, (2) the flatness of the resin surface produced, and (3) the speed of recoating. Recoating has been an important source of differentiation among competing laser photolithography products. There are essentially four approaches used in systems that build parts in a vat of polymer: deep dip, inverted "U," viscous retention, and positive displacement (Fig. 9.9).

The "deep dip" approach is perhaps the most widely used recoating method. As shown in Fig. 9.9a, the part is lowered into the vat by a distance greater than the intended layer thickness to promote the flow of a viscous resin over the surface of the part. The part is then raised to the height that it should be when the next layer is imaged, and a mound of photopolymer is created above the free surface of the resin in the vat. A blade then moves across and wipes the excess resin off to the side, leaving the desired layer thickness. This method is a substantial improvement over the previous method where gravity was relied on to level the surface (this was slow); however, it can be sensitive to part geometries such as that shown in Fig. 9.9a where there is a "trapped volume" of resin. As the blade wipes across, the resin in this volume may be shifted, with the result that the layer thickness after equilibration is not quite as desired. This method is used by 3D Systems and DMEC (DMEC's blade flips up at the end of a pass).

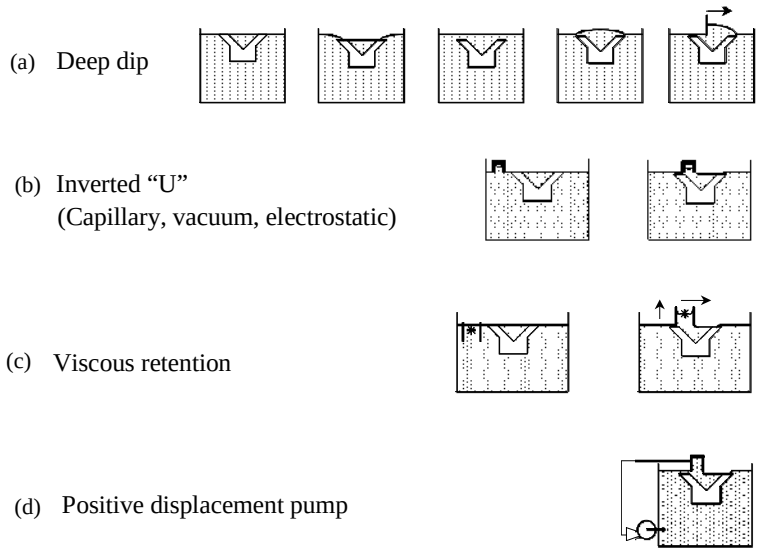


Fig. 9.9. Recoating methods in laser photolithography.

Fig. 9.9b shows the "inverted 'U'" approach, where a coating device is filled with resin above the free surface of the vat, and this resin is then dispensed as the coater traverses the vat. Filling of the inverted "U" can be by capillarity, electrostatics, or vacuum. The trailing edge of the recoater acts as a doctor blade. This method is relatively immune to the problem of trapped volumes and can be faster than the deep dip, since no stage is strongly dependent on gravity-induced flow. CMET uses capillary filling of the recoater (although there may have been a communication problem on this issue). Fockele and Schwarze uses the electrostatic method, although it apparently does not work equally well with all polymers. 3D Systems uses the vacuum method.

Fig. 9.9c shows the method of "viscous retention." A brush or mesh (depending on the resin) is supported between two doctor blades. While the layer is being imaged, this device is submerged in the vat. When it is time to recoat, it comes up and over the surface of the vat, and the material drains out by gravity as a rate determined by the viscosity of the resin. The final surface is created by the trailing doctor blade. Teijin Seiki practices this method.

Fig. 9.9d shows a positive displacement pump used to bring material up for the new layer. This method is used by EOS.

GROUP 3: ALL AXES MECHANICAL

A large number of RP machines fall into the classification, all axes mechanical (Fig. 9.10).

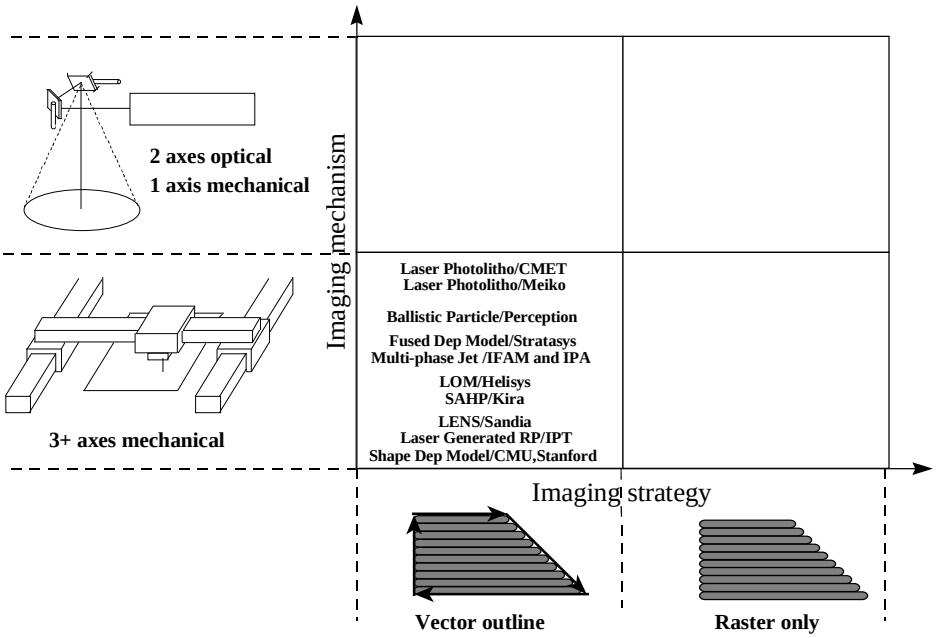


Fig. 9.10. Machines with all-mechanical imaging systems.

Mechanical Actuation

There is no predominant technology in use to effect the mechanical motions in RP machines. A wide variety of the technologies in general use for positioning in industry are in evidence in RP machines, with a focus on electrical actuation (as opposed to hydraulic or pneumatic actuation). Often a machine uses different approaches for its different axes. For example, the recoater in a laser photolithography machine might be cable-driven from a capstan, while the vertical axis is driven by a ball screw. In most cases, control is effected using either a stepper motor or a servo motor with a rotary encoder on the motor, but some cases also exist of linear encoding on a slide. In general, research organizations tend to buy integrated motion assemblies for their RP machines, but commercial organizations often buy the machine elements and do custom integration. For some vendors, this approach is dictated by cost; for others it is dictated by performance considerations.

Material Delivery

An important subset of the all-axes-mechanical RP machines have the feature in common that they deliver material. The device used to deliver material is generally a critical part of these technologies and often (perhaps always) embodies proprietary developments by the machine builder.

- In Fused Deposition Modeling (FDM) as practiced by Stratasys, the extrusion head must deliver the material at a well-defined temperature in order to promote bonding while maintaining the shape of the extrudate. Further, controlling the width of the "road" is critical to achieving dimensional control of the process.
- In Ballistic Particle Manufacturing (BPM) and in 3D Printing, the ink-jet printheads that are used to deliver material determine the geometry of the component. BPM adds the further demand of having to accurately control the temperature of the droplets of material so that they fuse properly to the part. In 3D Printing, taking full advantage of the capability of the process to print different materials in different locations requires the development of a printhead that can accommodate a range of binder materials.
- In the LENS process, in Laser Generated RP, and in other similar techniques, the technology used to deliver powder to the molten pool maintained by the laser is critical to achieving the desired material properties, and probably, to achieving z-axis dimensional control.
- In Shaped Deposition Manufacturing (SDM), the deposition nozzle is critical to achieving the desired material properties.

Sheet Machines

The class of machines that construct from sheet material is a subset of the all-axes-mechanical type. While it is possible to have a sheet machine that images optically, the nature and speed of the devices used to cut the outline of the sheet suggests that an all-mechanical approach is probably more suitable. Most of the cutting devices in use or under consideration are either fairly massive or have contact force interaction with the sheet. The exception is laser cutting, but in this case, cutting speeds are slow compared to imaging in a stereolithography vat, and mechanical actuation has some advantages in this regime of operation.

Table 9.3 summarizes the interesting contrast that may be drawn between two different approaches to building with paper as the feedstock, as practiced in the Helisys LOM process and in Kira's SAHP (selective adhesive and hot press) process, which represents a highlight in new machine configurations in Japan.

Table 9.3
LOM/Helisys vs. SAHP/Kira

	LOM	**SAHP**
Work area	500 x 760 mm	280 x 400 mm
Paper supply	Paper roll	Plain paper sheet
Lamination method	Hot roller	Hot press
Adhesive application	Preapplied to roll	Selective laser printer
Paper cutting	CO_2 laser	Knife plotter
Work environment	Lab or shop floor	Office

LOM can make quite large parts from a roll of paper as feedstock. In LOM the adhesive is preapplied to the roll and a new layer is added to the stack by hot roll lamination. A laser is used to cut the sheet. The use of the laser restricts this process to a lab or shop floor. The strength of the SAHP machine is that it assembles commercially available imaging tools in an office environment. The machine works from cut-sheet paper and

selectively applies the adhesive with a laser printer. After hot press lamination, the sheet is cut with a knife plotter using a carbide knife. The chief weakness of the SAHP machine is that it is limited in size by the need to purchase a commercial laser printer, and Kira designers state that they have no intention of going beyond the size of their current machine. Minor limitations include the need to periodically replace the knife, and the fact that the paper used is sensitive to moisture.

Both LOM and SAHP make a cut that is nominally perpendicular to the sheet material. Another point of departure is to cut the sheet with beveled edges so as to reduce the stair-stepping effect. Work at Case Western Reserve in the United States is exploring 4-axis cutting with a laser. Most of this work has been done with tape-cast ceramic sheet (sheet made of particles held together by a polymer binder). In this case, the sheet is cut and then stacked; it would be difficult to imagine how bevel-cutting could be accomplished by stacking and then cutting, since the cut would have to terminate immediately after the first layer, and the long cut involved in a bevel cut would be difficult to control with the necessary accuracy. Work that started at MIT and continues at Rensselaer Polytechnic Institute is exploring alternate methods of 4-axis cutting of metal sheet, including laser, water jet, and machining techniques.

Professor Nakagawa at the University of Tokyo intends to build a metal lamination machine for large tooling. On the question of 2-axis versus 4-axis cutting he acknowledged the issues associated with cutting sheet with very small bevel angles; however, he did not indicate which approach he is pursuing.

GROUP 4: THERMAL PROCESSING

The final broad class of machines has in common the property that thermal processing plays a strong role during the RP process. This thermal processing role is crucial because of (1) the generation of thermal stresses in the part as it is being formed, and (2) the attainment of the desired physical properties of the part. Designing the equipment used to effect the thermal control is often one of the most challenging aspects of these processes.

In FDM, it has already been noted that control of the extrudate temperature is critical. In addition, however, the control of the temperature in the atmosphere around the part has been found to be important in controlling part distortion. Similarly, in laser sintering, the control of the environment and the powder is crucial to control of residual stress and distortion. This control is particularly challenging because the powder bed must be held at an elevated temperature so as to further reduce the generation of stress. In the processes that laminate sheet such as hot roll with LOM and hot press with SAHP, the design of these laminators so as to minimize the introduction of stress has been a major focus of machine design efforts. In SDM, minimizing the stress introduced when a new layer of material is applied is an important consideration. In the LENS process and other similar processes, no studies of residual stress have yet been conducted; however, it is possible that such stresses will be strongly dependent on processing parameters.

GENERAL OBSERVATIONS ON MACHINE DESIGN

- There is pioneering work in machine design taking place in all three regions surveyed, the United States, Europe, and Japan.
- At present, the regional best machine design is at rough parity in the three regions.
- Japan is working toward developing RP machines that can compete with CNC machines in performance (especially accuracy) and in price. At present, the focus of this work is on laser photolithography.
- There is a strategic issue of access to suppliers of lasers, scanners, and other critical components.

CHAPTER 10

METAL CASTING APPLICATIONS

Clinton L. Atwood

OVERVIEW OF THE INVESTMENT CASTING PROCESS

Investment casting, often called lost wax casting, is regarded as a precision casting process to fabricate near-net-shaped metal parts from almost any alloy. Although its history lies to a great extent in the production of art, the most common use of investment casting in more recent history has been the production of components requiring complex, often thin-wall castings. While a complete description of the process is beyond the scope of the discussion here, the sequential steps of the investment casting process will be briefly described, with emphasis on casting from rapid prototyping patterns.

The investment casting process begins with fabrication of a sacrificial pattern with the same basic geometrical shape as the finished cast part (Fig. 10.1a). Patterns are normally made of investment casting wax that is injected into a metal wax injection die. Fabricating the injection die often costs tens of thousands of dollars and can require several months of lead time. Once a wax pattern is produced, it is assembled with other wax components to form a metal delivery system (Fig. 10.1b), called the gate and runner system. The entire wax assembly is then dipped in a ceramic slurry, covered with a sand stucco (Fig. 10.1c), and allowed to dry. The dipping and stuccoing process is repeated until a shell of ~6-8 mm (1/4-3/8 in) is applied.

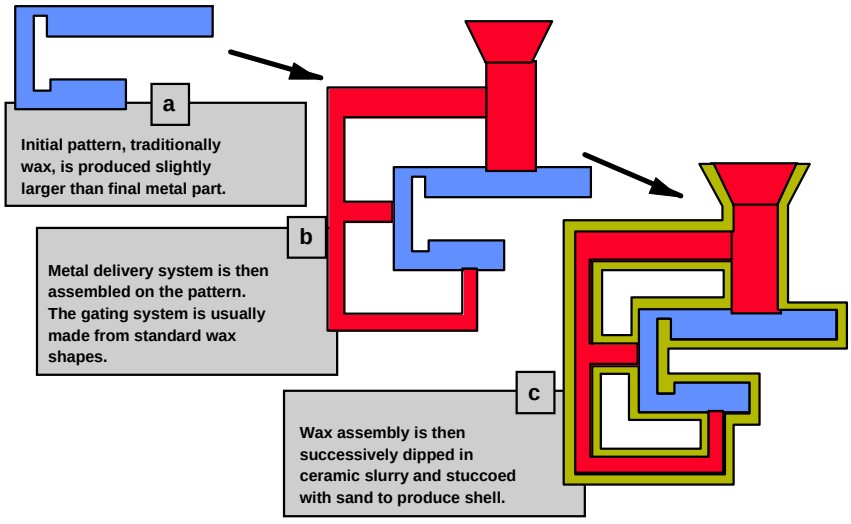


Fig. 10.1. Investment casting process description.

Once the ceramic has dried, the entire assembly is placed in a steam autoclave to remove most of the wax (Fig. 10.2a). After autoclaving, the remaining amount of wax that soaked into the ceramic shell is burned out in a furnace (Fig. 10.2b). At this point, all of the residual pattern and gating material is removed, and the ceramic mold remains. The mold is then preheated to a specific temperature and filled with molten metal, creating the metal casting (Fig. 10.3a). Once the casting has cooled sufficiently, the mold shell is chipped away from the casting. Next, the gates and runners are cut from the casting, and final postprocessing (sandblasting, machining) is done to finish the casting (Fig. 10.3b). Fig. 10.4 shows the CAD solid model, the shell, and the pattern produced in the QuickCast process.

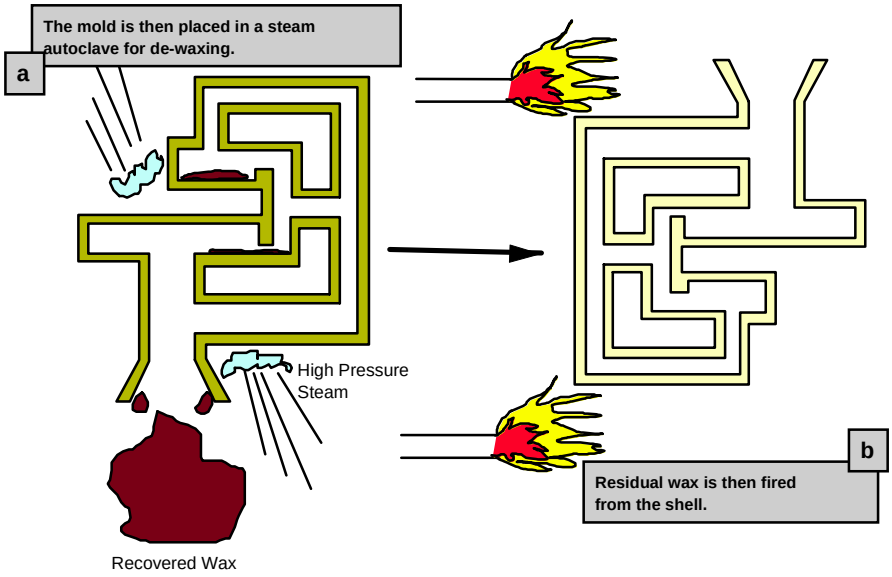


Fig. 10.2. Investment casting process description (cont'd.)

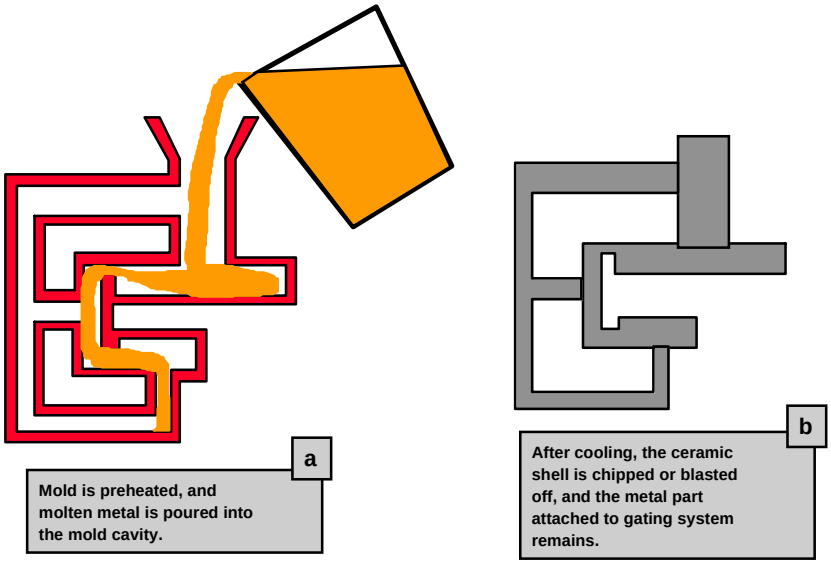


Fig. 10.3. Investment casting process description (cont'd.)

Fig. 10.4. CAD solid model (top), ceramic shell with QuickCast pattern (left), QuickCast pattern (right).

The major impact rapid prototyping processes have had on investment casting is their ability to make high-quality patterns (Fig. 10.5) without the cost and lead times associated with fabricating injection mold dies. In addition, a pattern can be fabricated directly from a design engineer's computer-aided design (CAD) solid model. Now it is possible to fabricate a complex pattern in a matter of hours and provide a casting in a matter of days. Investment casting is usually required for fabricating complex shapes where other manufacturing processes are too costly and time-consuming. Another advantage of rapid prototyping casting is the low cost of producing castings in small lot sizes.

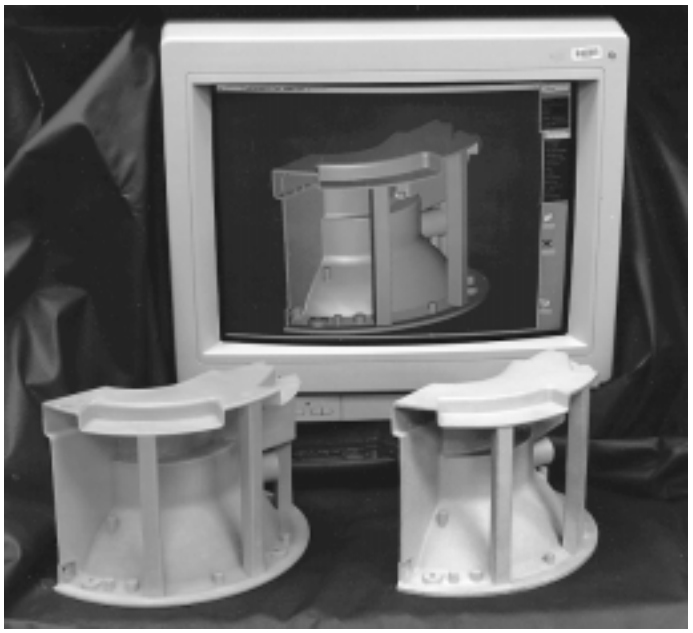


Fig. 10.5. CAD solid model (top), SLS polycarbonate pattern (left), A356 aluminum casting (right).

METAL CASTING APPLICATIONS IN THE UNITED STATES

Investment Casting

The United States is clearly the world leader in the use of rapid prototyping processes for metal casting applications. Metal casting from RP patterns is widely used by government and industry, cross-cutting numerous markets, including those for automotive, aerospace, medical, and consumer products. The use of RP patterns for investment casting continues to increase as processes evolve and pattern quality improves. There is already a significant number of U.S. companies applying RP to metal casting, as Table 10.1 shows. 3D Systems' stereolithography (SL) process is often used to fabricate patterns for investment casting. The QuickCast build style, coupled with CibaTool and other epoxy resins, is now used by many U.S. companies to fabricate complex patterns quickly for investment casting of metal parts. DTM Corporation's Selective Laser Sintering (SLS) process is used to fabricate investment casting patterns from several materials, including investment casting wax, polycarbonate, and a recently released proprietary material called TrueForm. The use of the SLS process to fabricate investment casting patterns continues to increase as material performance and accuracy improve. To date, however, far fewer SLS machines are in use than SL machines. Other RP processes used in the United States to fabricate investment casting patterns include Stratasys' Fused Deposition Modeling (FDM); Helisys' Laminated Object Manufacturing (LOM); Cubital's Solid Ground Curing (SGC); Sanders Prototype's Model-maker; and BPM (Ballistic Particle Manufacturing) Technology's process. The Soligen Direct Shell Production Casting (DSPC) process yields investment cast parts by directly fabricating an investment casting mold without the use of a pattern.

Table 10.1
U.S. Rapid Prototyping Manufacturers' Applications for Metal Casting

Rapid Prototyping Process	Metal Casting Application
3D Systems Stereolithography	QuickCast patterns for investment casting Epoxy patterns for precision sand casting and soft tooling
DTM Selective Laser Sintering	Investment casting wax, polycarbonate, and TrueForm patterns for investment casting TrueForm, composite nylon, polycarbonate for precision sand casting and soft tooling RapidTool for hard tooling investment casting patterns
Stratasys Fused Deposition Modeling	Wax patterns for investment casting
Helisys Laminated Object Manufacturing	Laminated paper master patterns for sand casting, limited use for investment casting
Soligen Direct Shell Production Casting	Ceramic investment casting mold fabricated directly from CAD solid model
Cubital Solid Ground Curing	Patterns for flask mold casting; process for fabricating wax investment casting patterns under development
BPM Ballistic Particle Manufacturing	Wax patterns for investment casting
Sanders Model-Maker 3D Plotting	Wax patterns for investment casting

METAL CASTING APPLICATIONS IN EUROPE (GERMANY AND FRANCE)

In Europe the use of RP for investment casting is limited but increasing. As the use of CAD solid modeling increases, application of rapid prototyping for manufacturing metal investment castings will also increase. Table 10.2 summarizes some German-manufactured rapid prototyping systems.

Table 10.2
German Rapid Prototyping Manufacturers' Applications For Metal Casting

Rapid Prototyping Process	Metal Casting Application
Electro Optical Systems (EOS) Stereos Laser Stereolithography	Investment casting patterns fabricated using Skin & Core software and AlliedSignal Exactomer resin
EOSINT P Laser Sintering	Investment casting patterns fabricated using polystyrene material developed jointly with the University of Stuttgart IKP
EOSINT S Laser Sintering	Sand casting molds and cores fabricated directly from CAD solid model using polymer-coated green sand

Dassault Aviation (France) is a frequent user of RP patterns for investment casting. In the same manner as many U.S. companies, Dassault designs and manufactures complex metal castings using 3D Systems' QuickCast build style to fabricate patterns. Dassault engineers have worked with several foundries to develop process parameters for successfully casting RP patterns. Dassault has certified RP castings for use in testing prototype flight hardware. In addition, some German companies use the expertise of Dassault to get metal castings from RP patterns.

The European automotive industry has also had success using RP castings. Typically, a company sends a CAD solid model of the design to the United States for pattern fabrication, a U.S. foundry does the casting, and the part is delivered back to the company. One such successful case study is documented in the recently published book *Stereolithography and other RP&M Technologies* (Jacobs 1996). Mercedes-Benz Division of Daimler-Benz designed a new four-cylinder engine block using CATIA solid modeling software. The solid model design of the full-size engine block was sent to 3D Systems Technical Center in Darmstadt, Germany, for pattern fabrication. The completed investment casting pattern was then sent to Solidiform, Inc., in Dallas, Texas, for investment casting. The completed aluminum casting was then sent back to Mercedes-Benz, resulting in a significant savings in time and cost.

Schneider Prototyping, the largest service bureau in Germany, has developed a proprietary process for casting metal parts from the Cubital SGC process. Metal castings account for 15-20% of Schneider's work. Cubital is developing a process for fabricating wax patterns by capturing a wax shape within a thin polymer coating.

The Fraunhofer Institute for Applied Materials Research (IFAM) currently uses the Stratasys FDM process to fabricate wax patterns for investment casting. It is also involved in a demonstration project for investment casting of custom medical implants in a joint effort with a medical clinic, an implant manufacturer, and an investment casting foundry.

Electro Optical Systems (EOS), a manufacturer of rapid prototyping systems, is developing processes and materials focused on metal casting applications.

Research and Development

Cubital is developing a process for fabricating wax patterns for investment casting by capturing the wax shape within a thin polymer coating. The polymer coating is subsequently removed, leaving the wax pattern.

Conclusion

The enabling technology for use of rapid prototyping processes is CAD solid modeling. The CAD solid model captures the geometry, which can be easily processed in any RP machine. The use of CAD solid modeling in Europe is not widespread; however, its use and application are increasing. As the use of solid modeling and rapid prototyping increases, the use of investment RP patterns is increasing as well. European

RP manufacturers recognize the potential for metal casting applications and are developing new processes and materials for use in metal casting. In addition, German foundries are learning to cast RP patterns. They have had more success casting polystyrene patterns than stereolithography QuickCast patterns.

METAL CASTING APPLICATIONS IN JAPAN

As in Germany, the use of CAD solid modeling in Japan is limited. Again, as the enabling technology for rapid prototyping machines, a CAD solid model must be created before a part can be fabricated. The use of two-dimensional CAD is very common in Japan. Often a 2D CAD file is translated to a 3D CAD solid model, then fabricated on an RP machine, but the extra step of creating the solid model increases the cost of the RP part. In Japan, rapid prototyping competes with machining for producing prototype parts. In many cases, even complex geometries can be machined as fast as parts can be fabricated using RP. There are hundreds of small machine shops in Japan, and the competition for work makes machining an attractive alternative to RP. Another reason RP competes with machining is the lower accuracy and surface roughness limitations of RP parts. As the use of CAD solid modeling increases, the use and application of RP is expected to increase. This was evident by the use and application of RP in some of the small progressive companies that the JTEC/WTEC panel visited.

Table 10.3 summarizes some of the rapid prototyping systems in use in Japan.

Table 10.3
Japanese Rapid Prototyping Manufacturers' Applications for Metal Casting

Rapid Prototyping Process	Metal Casting Application
CMET Solid Object Ultra-violet laser Plotter (SOUP)	Epoxy investment casting patterns fabricated using proprietary software that generates triangle or rectangle hatches to build quasi-hollow patterns. This process is also used to fabricate solid patterns for sand casting.
Design Model Engineering Center (DMEC) Sony Solid Creator	Investment casting patterns fabricated in Sony process using JSR polyurethane acrylic resin
Teijin Seiki Soliform Solid Forming System	Teijin Seiki is working with DuPont to develop a new resin (SOMOS 4100) for use in fabricating patterns for investment casting.
Kira Solid Center/Selective Adhesive and Hot Press Process (SAHP)	Laminated paper patterns for sand casting
Meiko	Plaster casting patterns for Japanese jewelry industry using a relatively low-accuracy photo-resin system. Process is used to fill void from lack of skilled craftsmen to make patterns.
Denken	(There was no mention of the use of Denken's process for metal casting applications.)

INCS, Inc., is the largest service bureau in Japan. It uses 3D Systems stereolithography machines to build QuickCast patterns for investment casting. This accounts for approximately 15% of its work. INCS engineering staff and technicians are very knowledgeable about RP, and the parts that they displayed to the panel are of excellent quality. The company has worked with investment casting foundries to cast the CibaTool 5180 epoxy QuickCast patterns. According to INCS' staff, there are five foundries in Japan capable of casting RP patterns. They also stated that investment casting in Japan is a $600 million industry.

Nakamura Pattern Company is a small pattern making company that has 20-25 employees. As a traditional sand casting pattern builder, most of its employees are skilled pattern makers. However, this group of skilled pattern makers is advancing in age (the average age is 50 years), and the company is having trouble attracting replacement workers to be trained as skilled pattern makers. As a result, Nakamura Pattern Company owners decided to investigate RP as a limited alternative to traditional hands-on pattern making. They visited the United States and attended the SME/RPA Rapid Prototyping and Manufacturing Conference and Exposition in Dearborn, then toured several U.S. companies, including Helisys. After thorough investigation of several rapid prototyping processes, Nakamura chose to purchase a Helisys LOM machine.

Nakamura has integrated the LOM machine into its manufacturing base, using it for fabricating complex patterns for sand casting. It is run on a 24-hour basis. Right next to it is a CNC (computer numerical control) wood-milling machine. Depending on accuracy requirements, the company chooses between CNC machining and the LOM machine for pattern fabrication. CNC is used for greater precision, but the LOM machine is easier to use. Company representatives estimate that using the LOM machine has increased business by 50% (Sites, 1996, 92-94).

One of Nakamura's advantages in using rapid prototyping to fabricate sand patterns is that it is actively using CAD solid modeling. The company uses several types of CAD solid modeling software, and its staff is well trained. This company has been very progressive in its use of new technology (RP and CNC); at the time of the JTEC visit, its management intended to look into purchasing another LOM machine within the next year or so.

Toyota Motor Corporation is in the process of evaluating rapid prototyping for metal casting. It has done some benchmarking with selective laser sintering and stereolithography as well as LOM, and it is just now looking at metal casting applications. Preliminary results of Toyota's benchmarking indicate that there are limitations to each of the RP processes it is investigating. It, too, is comparing CNC machining to rapid prototyping.

Hino Motors, Ltd. is a user of 3D Systems stereolithography apparatus (SLA-500). It is currently in the process of upgrading its machine to build investment casting patterns using QuickCast software and CibaTool 5180 epoxy resin. Its engineers also see potential in the use of solid stereolithography patterns for sand casting applications. Evaluation of this application is underway.

Tokuda Industries uses the Kira Solid Modeler to make paper patterns for sand casting. Tokuda representatives stated to JTEC/WTEC panelists that there were some drawbacks to this process, in that it requires attended operation, and the accuracy and surface quality are less than desirable. They also stated that although the Kira process is less expensive, it is slower than CNC milling.

Research and Development

As previously stated, research and development for metal casting applications in Japan is primarily focused on materials and software development for pattern fabrication. There has been some R&D done by Professor Nakagawa in the area of casting and computer simulation. This work is documented in a paper "Applications of Laser Stereolithography to Casting and Computer Simulation" (Nakagawa et al. n.d.).

Conclusion

In Japan, CAD solid modeling is not widely used. In many cases, part designs have to be translated into solid models before fabrication by a rapid prototyping machine. This increases the cost of RP parts. Rapid prototyping is compared to (and competes against) CNC machining with respect to cost, scheduling, and quality. Insufficient accuracy and surface quality of parts fabricated using RP processes are limiting their use in Japan. Small progressive companies like Nakamura Pattern Company and INCS are aggressively and successfully using rapid prototyping for metal casting applications.

REFERENCES

Jacobs, P. F. 1996. *Stereolithography and other RP&M technologies.* Dearborn, Michigan: Society of Manufacturing Engineers (in cooperation with the Rapid Prototyping Association of SME and the American Society of Mechanical Engineers, New York).

Maguire, M. C., M. D. Baldwin, C. L. Atwood, B. T. Pardo. 1995. *Rapid prototyping technologies and their application to metalcasting.* American Metalcasting Consortium.

Nakagawa, T., et al. n.d. Applications of stereolithography to casting and computer simulation. Tokyo, Japan: University of Tokyo Institute of Industrial Science, and Saitama, Japan: Institute of Physical and Chemical Research.

Sites. 1996. This reference designates the companion volume to this JTEC/WTEC report: Prinz, F. B., ed. *JTEC/WTEC panel report on rapid prototyping in Europe and Japan.* Vol. II. *Site reports.* Baltimore, MD: Loyola College. NTIS Report #PB96-199583.1

CHAPTER 11

TOOLING APPLICATIONS

Richard F. Aubin

INTRODUCTION

In the United States today, there is a greater variety of rapid prototyping tooling applications than in most other countries. U.S. engineers, scientists, technicians, and business people seem to brainstorm this relatively new technology in aggressive ways to try to find an appropriate fit for various applications. In so doing, they have found novel and creative applications of rapid prototyping (RP) to the manufacture of parts and tools.

The JTEC/WTEC panel visited a number of European and Japanese academic and commercial organizations performing excellent and interesting work in the application of RP to tooling. Their programs cover a variety of applications of RP technologies and the manufacture of various tools. This chapter reviews the applications that the JTEC/WTEC panel observed in Europe and Japan. While the panel found many of its hosts to be open and casual, it should be acknowledged that organizations' natural propensity to protect their intellectual property is especially visible in rapid prototyping application development. Although the rapid prototyping equipment is in the public domain, how this technology is applied to attain competitive advantage remains sensitive. Accordingly, the following information is a reflection of what was considered nonproprietary by the panel's hosts. It is to be expected that there are a lot more proprietary tooling application efforts underway than were shared with the panel.

There are a number of special considerations when applying rapid prototyping to tooling. In some cases, parts or tools must be plated with a thin coat of metal to facilitate their use in a harsh environment. In other cases, it is necessary to fabricate holding fixtures for parts to be inspected in coordinate measuring machines (CMM), or to hold parts that will be machined via electronic discharge machining (EDM). Even though it is possible to render a fixture that can hold a complex delicate part for some touch-probing inspection directly from a computer model, or to EDM a part with little to no tool pressure on the part, there is a certain amount of cultural change that is necessary before manufacturers or their clients are ready to take this step. Manufacturers need to be convinced that if there is not a lot of pressure on the tool, and it is just going to be holding something statically positioned, a plastic tooling fixture will suffice in place of a metal fixture. It is in willingness to embrace this kind of cultural change that the panel feels the United States is, in general, further ahead than the European countries and Japan. However, there is a considerable amount of innovative RP tooling work underway in France, Germany, and Japan.

RAPID PROTOTYPING TOOLING APPLICATIONS IN EUROPE

The JTEC/WTEC panel visited 11 sites in Europe that have RP tooling applications (all are in Germany, except as noted):[1]

1. Fraunhofer Institute for Manufacturing Engineering and Automation (IPA), Stuttgart
2. Fraunhofer Institute for Chemical Technology (ICT), Pfinztal
3. Fraunhofer Institute of Applied Materials Research (IFAM), Bremen
4. Fraunhofer Institute for Production Technology (IPT), Aachen
5. Institute for Polymer Testing and Polymer Science (IKP), University of Stuttgart
6. The Bavarian Laser Center (BLZ), Erlangen
7. Catholic University of Leuven and Materialise Co. (both of Belgium)
8. EOS (Electro Optical Systems), Munich
9. Cubital (and Schneider Prototyping), Bad Kreuznach
10. Laser 3D and Dassault Aviation, Villers-Les-Nancy (France)
11. Daimler-Benz, Sindelfingen

Seven Fraunhofer institutes, with financial support from the German government, are cooperating in a rapid prototyping network to speed up the development, advancement, and dissemination of rapid prototyping technologies to improve the competitiveness of the German manufacturing industry. (The main emphasis of this network is metallic prototypes; see Chapter 6.) The seven Fraunhofer institutes are the four listed above, and the following three (not visited by the panel):

1. Fraunhofer Institute for Graphic Data (IGD), Darmstadt
2. Fraunhofer Institute for Laser Technology (ILT), Aachen
3. Fraunhofer Institute for Production and Construction Technology (IPK), Berlin

What the JTEC/WTEC panel learned in its interviews at the Fraunhofer Institutes is that they are all very well prepared. The Fraunhofer Institutes have a broad knowledge base, a lot of experience, and a lot of shop-smart expertise. The developments underway at their facilities should not be underestimated.

Although there are various cooperative arrangements between them, each of the Fraunhofer Institutes focuses on a different issue: one takes software, another material development, still another focuses on applications, etc. The JTEC/WTEC panel found that by using this approach, the institutes are building a comprehensive infrastructure for rapid prototyping. The Fraunhofer labs are pristine, with brand new equipment. However, they had few parts at the time of the panel's visit, because they are just developing their infrastructure. The panel expects that once the laboratories are fully in place, they will be a strong force. Their integrated information model for rapid prototyping as shown in Fig. 11.1 is very impressive and worthy of note. There is nothing comparable in the United States.

Fraunhofer Institute for Manufacturing Engineering and Automation (IPA)

There is continued work at IPA on reverse engineering, or the use of physical models as computer input data. Some of this work was initiated during the Intelligent Manufacturing Systems IMS test case program of 1993. Here, laser scanning, optical and tactile measurement systems, X-ray computer tomography, and 3D ultrasonic sensors are applied for the shape digitizing of models to create a point cloud, which is then fed back into a CAD system to generate a CAD model for further evaluation. In an interesting development, IPA researchers are now working on integrating that process with software tools for surface segmentation, point cloud management, and curve fitting to virtual prototyping and physical prototyping. See Figs. 11.2a and 11.2b.

[1] See also the individual site reports in Sites 1996.

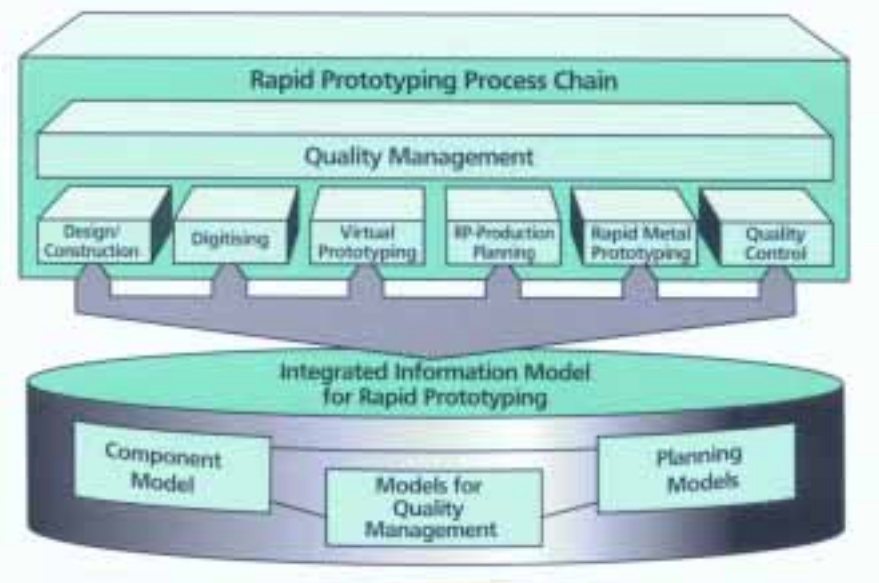


Fig. 11.1. The Fraunhofer integrated information model for rapid prototyping.

Fig. 11.2a. Scanned point cloud model.

Fig. 11.2b. Solid model from scanned data.

Researchers at IPA are also investigating coating technologies by applying metallic coating to stereolithography plastic parts for applications like EMI shielding and tooling. The coating processes include PVD, electroplating, and electrolysis plating. One benefit of coatings is that when an otherwise fragile component is coated with a metal, it acquires new characteristics and can be capable of withstanding harsher environments for downstream applications. This allows the part, component, or tool to be useful in new applications. Another benefit of coatings is that they can fill in the staircasing of the part, providing a smoother surface.

Another useful development at IPA is in the area of information and organization. IPA uses a quality function deployment (QFD) approach (Fig. 11.3) for selecting the most appropriate rapid prototyping technology.

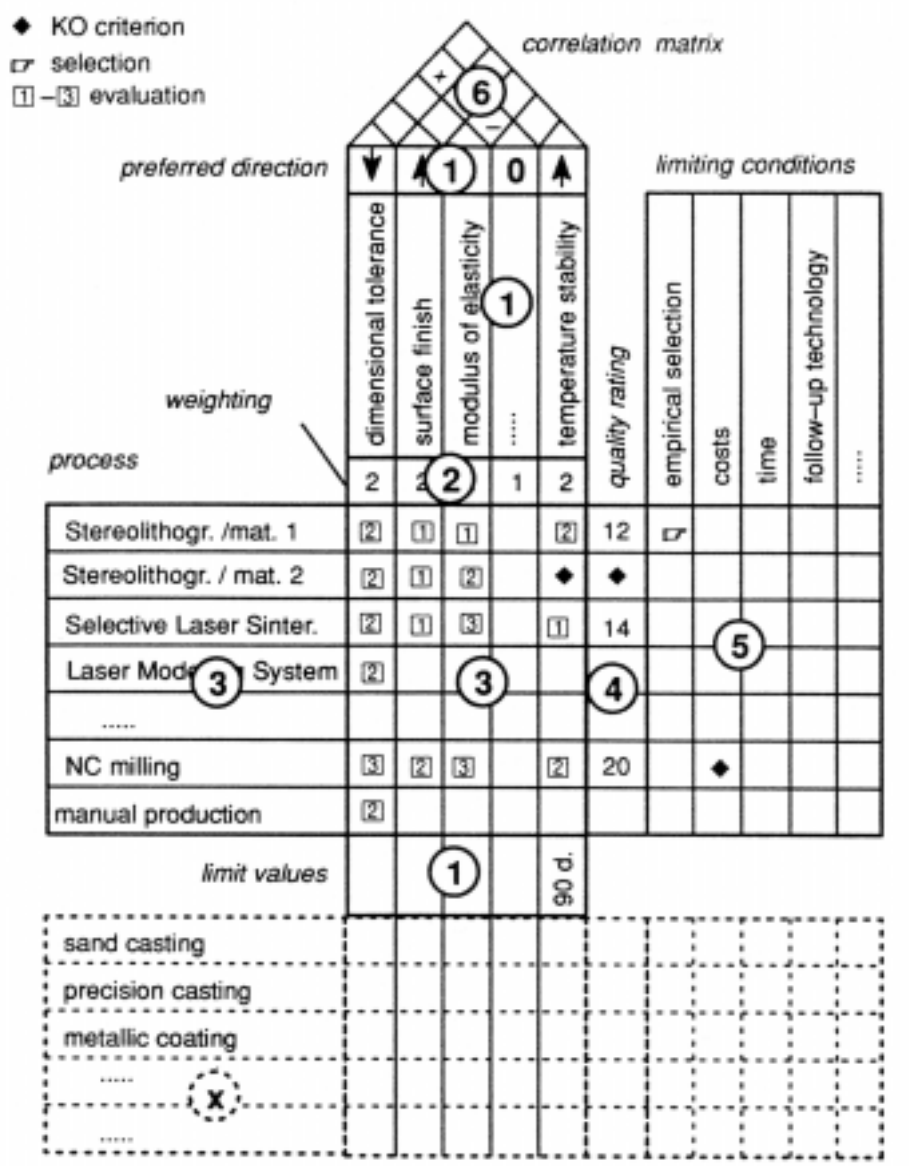


Fig. 11.3. Quality function deployment (QFD) approach to selecting most appropriate RP technology.

Although this work is not being done in the area of tooling at the present time, it certainly can be, with potentially very beneficial results. If the tooling industry can have an intelligent selector based on a tool's features and other requirements, designers will be able to very quickly determine what best fabrication approach to use for tooling or for casting, as well as what materials to use, and so forth. This could be one of the measures that could tie into a STEP application protocol, as discussed in Chapter 8. There are numerous potential applications and implications for IPA's QFD approach.

Fraunhofer Institute for Chemical Technology (ICT)

At ICT, the JTEC/WTEC panel found an example of rapid prototyping being used to make the cavity and core of a plastic injection mold. ICT researchers are making the mold inserts to go into a steel mold set. In this case, the mold is for an electrical receptacle. Using the 3D Systems stereolithography SLR-5180 epoxy resin, they were able to process some 200 parts in a variety of materials, including the following:

- polystyrene at 240ºC, 1,000 Bar, 40-second cycle
- ASA at 210ºC, 900 Bar, 40-second cycle

Their next step is to try to find ways to integrate the use of additional core pulls or slides so that they can mold more complex geometric features. Fig. 11.4 shows the mold cavity.

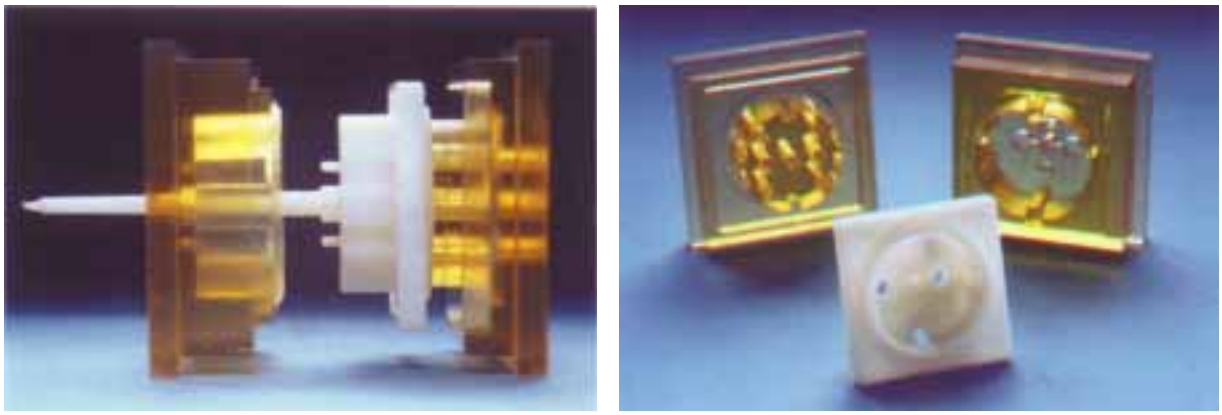


Fig. 11.4. Stereolithography mold cavity and core from ICT.

Fraunhofer Institute of Applied Materials Research (IFAM)

Researchers at IFAM are using the Stratasys Fused Deposition Modeling (FDM) process to make substrates. This process is akin to making the reverse of the desired part. Using an electroplating process that does not provide stress or heat, metal is applied on the back side of the part. After building a certain amount of metal on the back side of the part, it is back-filled with an epoxy material, aluminum shot material, or some other material to hold it so that it can be used as an injection mold, which has a 3 mm thickness of metal cladding interface between the mold and the back filling. Using the EOSINT laser sintering process, IFAM researchers are making molds with the Electrolux powder and infiltrating with $PbAg_2Sn_2$. This allows for a greater number of parts to be produced from the tool. Over 300 parts were processed from a single mold made from an ABS glass-filled nylon. Fig. 11.5 shows a sample tool and part.

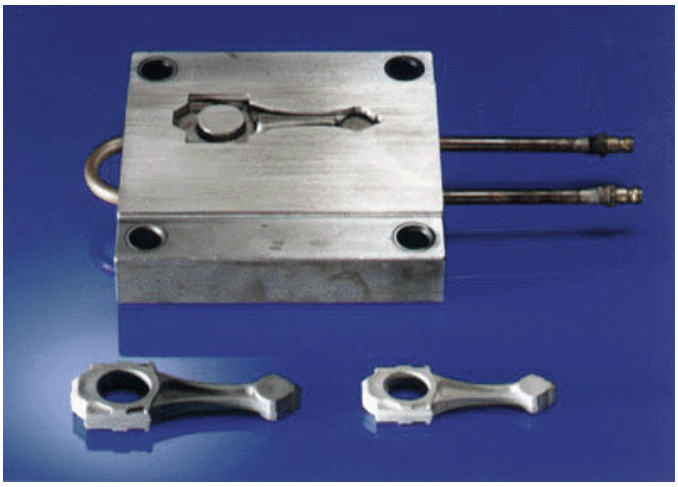


Fig. 11.5. Tooling for injection molding produced by FDM and electroplating at IFAM: tool (mold half) at top, produced green part (connecting rod) at bottom left, and sintered part at bottom right.

Fraunhofer Institute for Production Technology (IPT)

Chapters 2 and 6 discuss the laser-generated rapid prototyping under development at IPT. There, researchers are integrating the powder deposition approach with the use of a laser, followed by NC machining of the top surface and the periphery in a layer-by-layer fashion. IPT is now working with a die-casting company to commercialize this technology.

JTEC/WTEC panelists feel that IPT scientists, by combining their RP expertise with their extensive knowledge and capabilities in tooling, conventional laser and ultrasonic machining, and advanced grinding techniques, have great potential to develop new RP processes that overcome many current limitations.

Institute for Polymer Testing and Polymer Science (IKP), University of Stuttgart

IKP researchers are not particularly interested in investigating the various mold conversion techniques; they prefer to directly fabricate the mold using EOS stereolithography. As at ICT, researchers at IKP are fabricating the mold inserts directly from the computer model, but then putting them into a steel mold set reinforced with aluminum shot and epoxy. They have produced about 200 parts with this technique for Mercedes-Benz. The parts, however, show signs of deterioration and mold flash. For low-volume production this has proven to be efficient in terms of both time and cost.

The Bavarian Laser Center (BLZ)

BLZ conducts a variety of development efforts with lasers. Among the BLZ projects is one on laser sintering of EDM electrodes, as shown in Fig. 11.6. The process uses an EOS machine and Electrolux bronze alloy for the electrode material. The electrodes will be used for injection mold tooling and for forge dies. By creating some of these electrodes directly, using the laser sintering process, and then using these electrodes in EDM machines, it is possible to burn the shape into the forge die that is then used to forge parts.

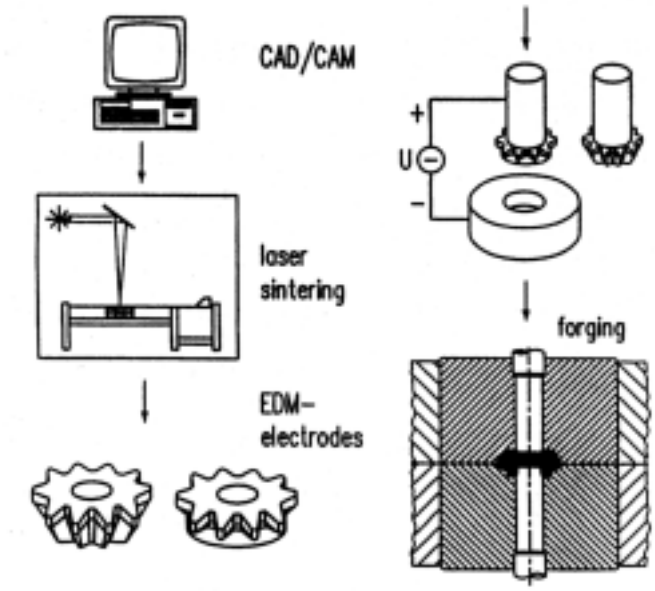


Fig. 11.6. Rapid prototyping of EDM electrodes for forge dies.

BLZ researchers are also developing a laminated process for sheet metal, where the laser cuts sheet metal layers that are then bolted together to form a tool insert. In addition, BLZ researchers are working on a process that uses the heat from a laser to selectively heat sheet metal to form and shape the sheet metal.

In another project, BLZ researchers are continuing development on a metal-removal process called lasercaving, which was originally invented by Maho (see also Sites 1996, 1-3). It appears that BLZ is investigating ways to integrate rapid manufacturing and sintering of tools and parts, using the lasercaving process to do the finish machining. The JTEC/WTEC team and the BLZ representatives had a lot of discussion about such "hybrid processes," where the rapid manufacturing processes of making components are integrated with the removal processes to do final finishing, in order to achieve both the accuracy and the surface finish required.

Catholic University Leuven (KU Leuven) and Materialise

A large variety of molding applications are under development at KU Leuven, in conjunction with its spin-off service bureau, Materialise. Most of these applications are quite well known to those in the fields of vacuum casting of polyurethanes in silicone rubber molds and spin casting of zinc die casting alloys in vulcanized rubber molds. KU Leuven and Materialise researchers are conducting research on including reinforcing fibers and woven glass mats that are transparent to the laser energy into the stereolithography resin, which make parts or tools more wear-resistant. Additional development is underway in selective laser sintering of metals for parts and tools and in rapid production of polymer injection molds and metal casting dies by 5-axis NC machining.

EOS

The EOSINT M (for metal) machine was developed to make metal molds using the Electrolux bronze powder. Some EOS customers are finding that they do not have to infiltrate the green sintered mold inserts for low-volume plastic injection molds with the solder. They can sinter the mold directly: it is strong enough to be used for some plastic injection mold parts, and the mold insert porosity does not prohibit molding. It is a fast and easy way to make tools that will suffice for a limited number of applications.

Cubital

Although Cubital did not have any direct applications for tooling at the time of the JTEC/WTEC panel's visit, company representatives acknowledged in discussions with panelists that the company has a program underway to develop epoxy materials that will accommodate tooling.

Laser 3D and Dassault Aviation

The cooperative work of these two French companies has produced very positive results. They have two programs that apply RP to tooling. The first is direct fabrication of a mold cavity using glass-filled resin, 70% of which consists of glass microspheres. These are used to make aluminum sand-casting mold halves for Dassault air-conditioning ducts (Fig. 11.7).

Laser 3D's second cooperative tool-making program with Dassault is the use of a stereophotolithography (SPL) master pattern in a 3D hydrotel tracing machine, where a control stick for the Mirage 2000 Fighter was machined in aluminum by tracing the SPL master pattern. The control stick had complex and ergonomic features. In this Laser 3D/Dassault SPL example, the hydrotel machine scans a plastic SPL part while it machines an aluminum replica. A hydrotel has a stylus and a milling cutter. The stylus motion on the part being traced also controls the motion of the milling cutter that is machining the duplicate of the scanned part. According to Dassault, this process has realized a three-fold cost savings compared to CNC machining.

Dassault provided a photo of a mold that was generated from Laser 3D master patterns (Fig. 11.8).

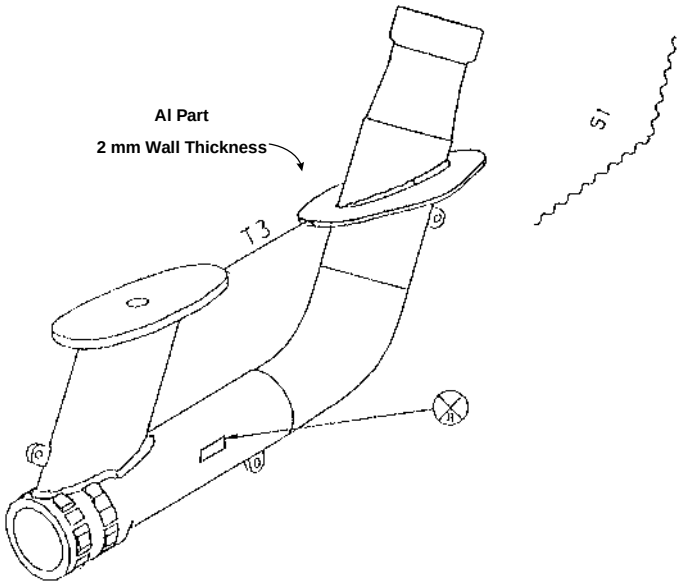


Fig. 11.7. Laser 3D patterns for Dassault air conditioning ducts.

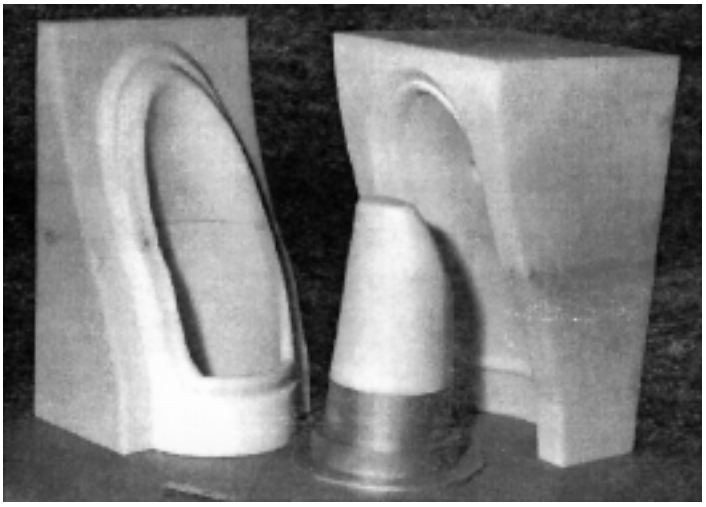


Fig. 11.8. Dassault mold inserts from Laser 3D master patterns.

Daimler-Benz

At Daimler-Benz, tooling is considered the most important application area for use of rapid prototyping technologies. This company is aggressively pursuing ways to make tools. Daimler-Benz participated in a study with IKP, noted previously, where an injection molding tool was fabricated directly from a 3 mm-thick stereolithography shell that was later backfilled with aluminum shot and epoxy resin. This tool produced about 200 injection-molded automotive parts. The mold inserts showed signs of wear, chips on corners, and some pitting. Nevertheless, in cases where only a few parts are needed for design verification of a new component under development, this process is a viable way to make a tool directly from a computer model at a reasonable cost.

RAPID PROTOTYPING TOOLING APPLICATIONS IN JAPAN

The JTEC/WTEC panel visited 14 sites in Japan that have RP tooling applications:

1. University of Tokyo
2. Tokyo Metropolitan Institute of Technology
3. D-MEC
4. Denken Engineering
5. Teijin Seiki
6. Kira Corporation
7. Tokuda Industries
8. INCS
9. Omron
10. Olympus Optical Company
11. Hino Motors, Ltd.
12. Shonan Design Company
13. Japan Aviation Electronics
14. Toyota

University of Tokyo

Professor Kimura of the University of Tokyo's Department of Precision Machinery Engineering noted in discussions with panelists that Japan has a long tradition of process improvement, or "*kaisan*." The Japanese are experts at incrementally improving manufacturing methods and processes to ultimate perfection. Professor Kimura told panelists that given time, an evolution of *kaisan* similar to what has taken place in manufacturing and production will certainly take place in Japan in rapid prototyping.

When panelists spoke with Professor Nakagawa of the Institute of Industrial Science at the University of Tokyo, he indicated his belief that the future of rapid tooling lies in the area of high-speed machining. There is extensive work in high-speed milling in Japan, and the Japanese are experts at its use and application. Professor Nakagawa's appraisal of the primary benefit of using rapid prototyping is that it can produce rapid design changes, especially for the electronics industry, which has a lot of different kinds of parts. Professor Nakagawa indicated that he is working on a new rapid prototyping process, which he hoped to be able to present in 1996. Professor Nakagawa provided a photo of a plastic injection mold tool (Fig. 11.9), that was fabricated by a DTM selective laser sintering machine for a project of the Ministry of International Trade and Industry (MITI).

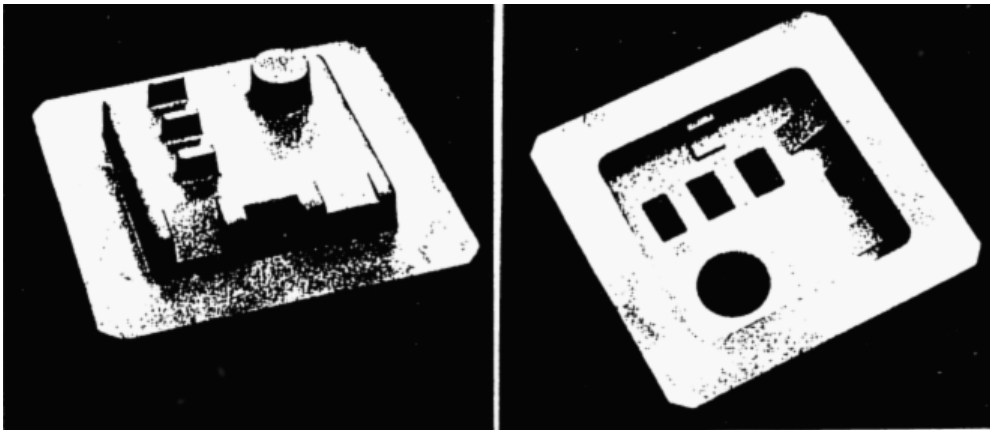


Fig. 11.9. Injection molding metal tool produced by DTM machine in Japanese MITI project.

Professor Nakagawa also provided a diagram showing how RP models are used in Japan to make molds and forming tools. See Fig. 11.10.

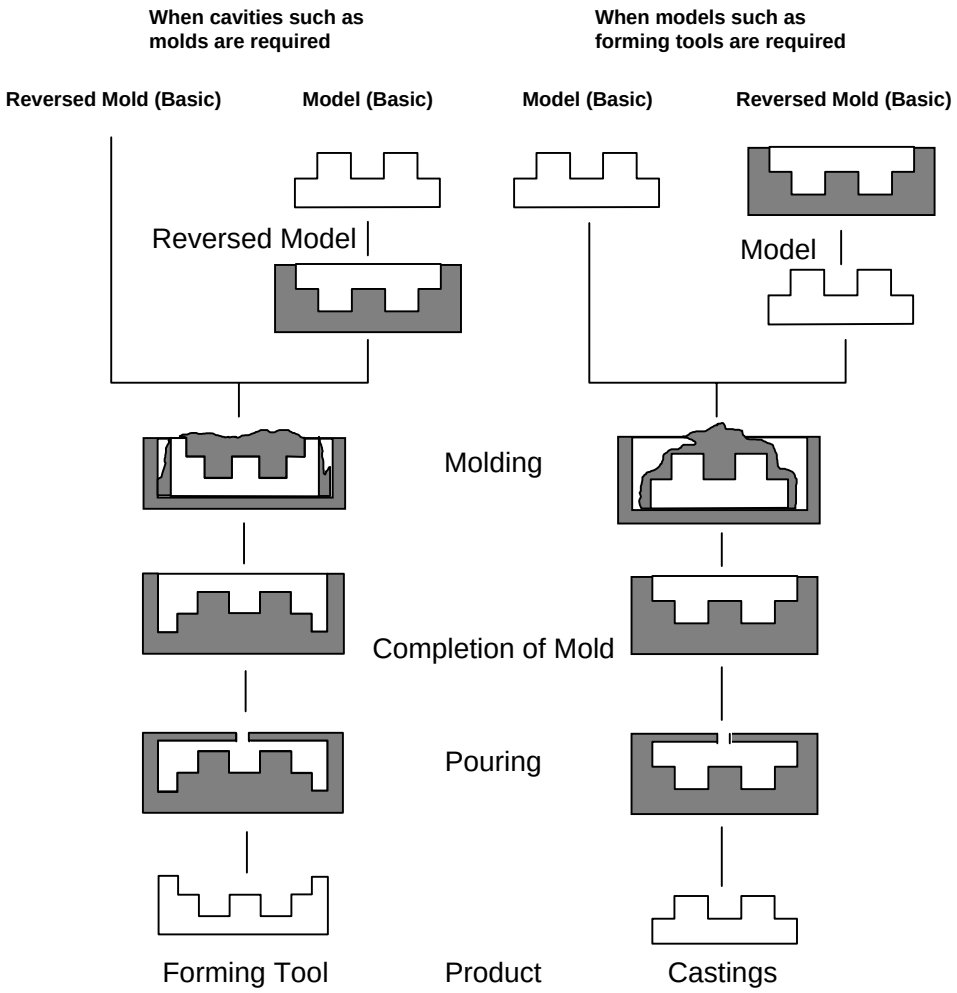


Fig. 11.10. Diagram showing how RP models are used in Japan to make molds and forming tools.

Tokyo Metropolitan Institute of Technology

Professor Fukuda of the Tokyo Metropolitan Institute of Technology is developing a CAD system that is more intuitive to users — one that is able to integrate changes and modifications so that the system can be worked with rapid prototyping and then integrated into virtual reality (VR). This could be very positive in the area of tooling.

Although this intuitive CAD approach is not an application that is available for rapid prototyping today, it has exciting possibilities. In the present system of producing a finished part, product engineers design the part, but they do not necessarily understand the process of producing the finished part. So when they finish a design and give it to the manufacturer, the manufacturing engineers must determine how to manufacture the part with considerations for expansion factors, holding targets, sequence of operations, and a number of other factors that the part designers are not concerned with. Traditionally, the product design goes from the design sector to the manufacturing sector, where the product is then processed and delivered.

With rapid prototyping and rapid tooling, the process variables noted above must still be accommodated, but can now be accommodated much earlier in the product development cycle. The research that Professor Fukuda is performing can be instrumental in capturing all of the process planning and bringing it up front into

the CAD model in an intelligent manner, so that it is not necessary to consult with various process experts to determine how best to make the tool or part. Professor Fukuda's project is highly relevant to tooling, because intricate planning for process variables is a reality that is not always recognized and appreciated, but nevertheless must be accommodated.

D-MEC

D-MEC is manufacturing glass-filled acrylate resins for plastic injection molds. The mold used was able to process about 180 ABS parts before heat distortion of the mold became unacceptable. D-MEC representatives showed the JTEC/WTEC team a lot of examples of using silicon rubber molds, spin-casting, and vulcanization, as well as a different process using a stereolithography master pattern and making a mold around it to make multiple copies. Several Japanese companies are already doing this.

Denken Engineering

Current applications at Denken are directed to the modeling environment. Engineering and tooling applications are a future goal. It appears that in engineering applications, rapid prototyping is primarily being focused on design verification. The Denken machine is a relatively low-cost, small-build-volume machine. The Ministry of Education in Japan subsidizes academic purchases for this equipment by up to 50%. That can be a terrific incentive for universities to get students to have a greater appreciation for all of the up-front RP processing variables that must be considered for manufacturing.

Teijin Seiki

Teijin Seiki is developing plastic injection molds for prototype applications using a 50-70% inorganic filled resin. The resin requires thermal post-curing.

Teijin Seiki is also using a vacuum casting application for a portable phone housing (Fig. 11.11).

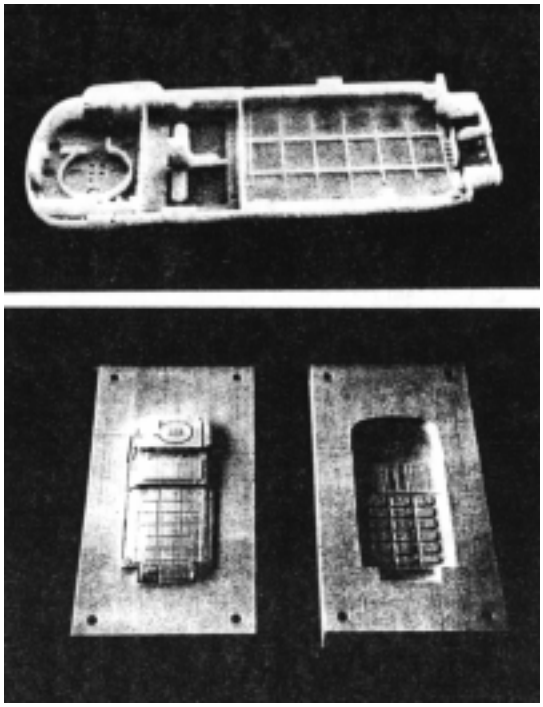


Fig. 11.11. Teijin Seiki filled resin mold to create an ABS phone housing component.

This tool required 40 hours of CAD design time, 14 hours on a Teijin Seiki Soliform machine, and 1 hour cleaning and post-curing, leading to a urethane casting in a lot size of more than 20 parts. In other RP work that is being accomplished in Japan, just preparing a CAD model requires half the time of making it, as in this example. Well over 50% of the production time was dedicated to making a "squeaky-clean" computer model, because without it, the machine cannot produce the desired finished parts.

Kira Corporation

Kira machine model KSC-50 was initially designed for design verification, not to be used as a tooling machine. However, Kira is finding that some of its customers are discovering creative and innovative ways to use the paper models as tools. Although accuracy is critical to tooling, several customers have successfully used the paper patterns as masters for silicone and epoxy molds, some of which are shown in Fig. 11.12. The Kira KSC-50 machine and its associated dimensions and specifications are provided in Fig. 11.13.

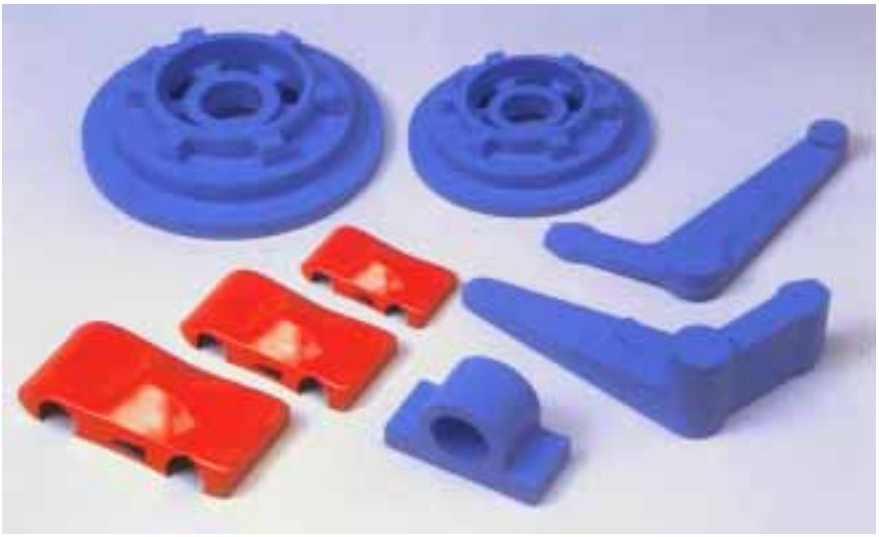
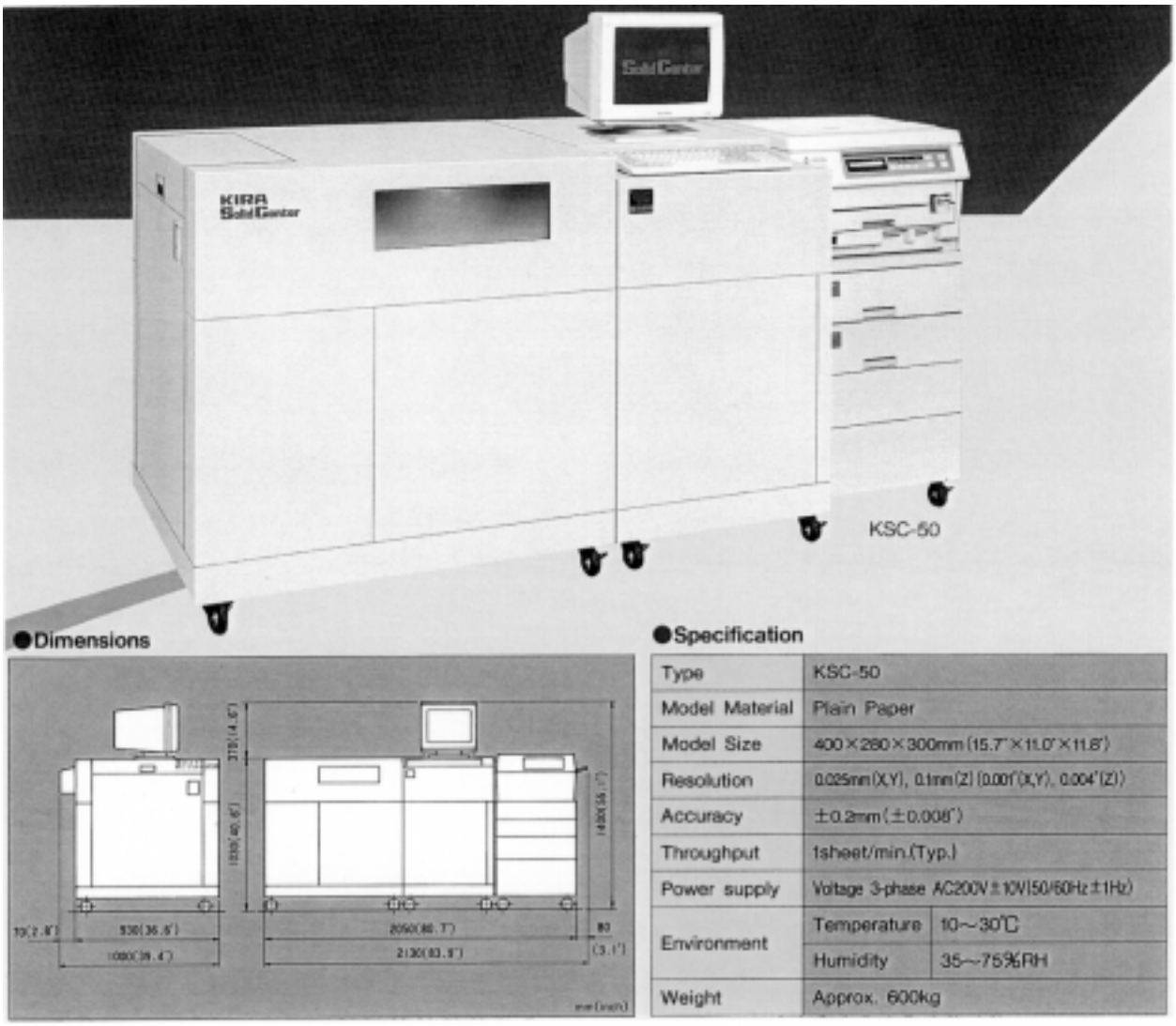


Fig. 11.12. Use of Kira Laminated Object Manufacturing (LOM) patterns for molds.

Tokuda Industries

Tokuda Industries, a prototype shop that fabricates models, forming tools, jigs, models for wind tunnel tests, and prototype products, was the first company to acquire the Kira KSC-50 machine. (It also has a CMET stereolithography machine.) Company representatives indicated to the JTEC/WTEC panel that for Tokuda, among the most appealing issues associated with rapid prototyping are its relatively low cost and low risk. The company provides early RP models of parts and or tools, gives them to customers with a quote for cost for the "machined part," and gets good value for that work. Tokuda's managers are very happy with this capability.

Tokuda representatives cited an example, also presented as a paper at a recent Japanese conference, of a sheet-metal die that measures 250 mm x 150 mm x 93 mm (Fig. 11.14). They compared the Kira RP machine capability to conventional numerical control (NC) machining in terms of (1) cost, (2) production time, (3) accuracy, and (4) cutting characteristics. The Tokuda representatives were favorably impressed with the lower cost and low risk of RP but disappointed in the time and dimensional accuracy of RP in comparison to CNC. They pointed to the need to correct for the staircasing effect of the stacked paper layers by coating the outside of the tool with a filler material, followed by manually sanding it smooth. Fig. 11.15 shows these steps.



Type	KSC-50	
Model Material	Plain Paper	
Model Size	400×280×300mm (15.7"×11.0"×11.8")	
Resolution	0.025mm(X,Y), 0.1mm(Z) (0.001"(X,Y), 0.004"(Z))	
Accuracy	±0.2mm (±0.008")	
Throughput	1sheet/min.(Typ.)	
Power supply	Voltage 3-phase AC200V±10V 50/60Hz±1Hz)	
Environment	Temperature	10~30℃
	Humidity	35~75%RH
Weight	Approx. 600kg	

Fig. 11.13. The Kira KSC-50 machine and its associated dimensions and specifications.

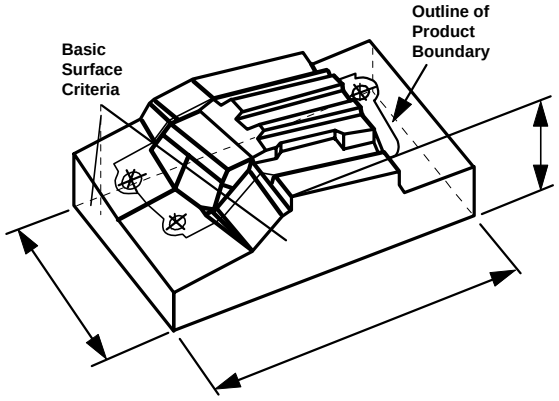


Fig. 11.14. Model of a sheet metal die from Tokuda Industries.

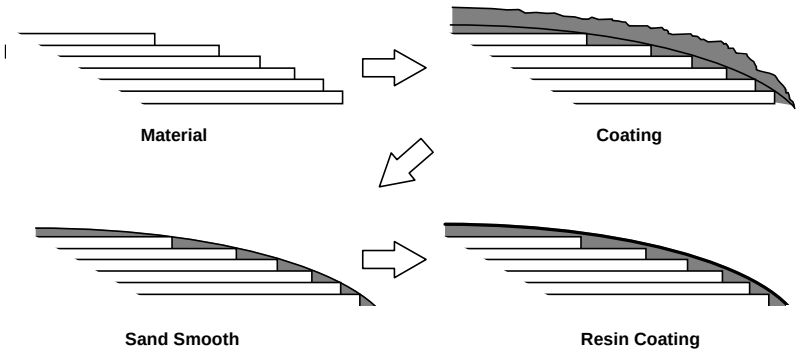


Fig. 11.15. Tokuda's steps to improve staircasing surface finish.

Fig. 11.16 compares the Laminated Object Manufacturing (LOM) with CNC machining in terms of cost and time. The cost of using the Kira process in comparison to CNC machining is less; however, the Kira RP process is slower.

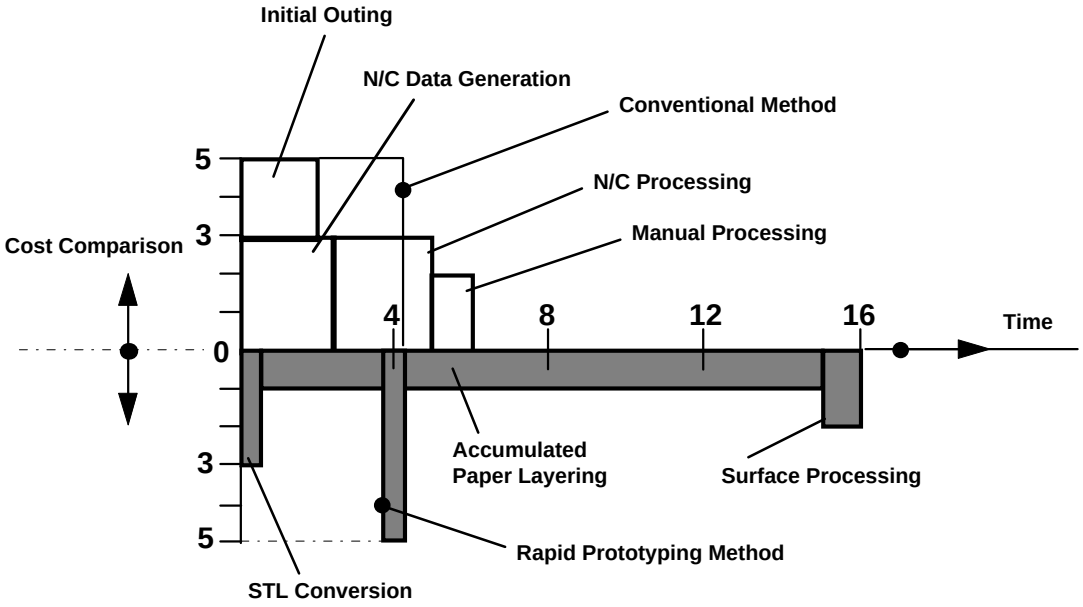


Fig. 11.16. Time and cost comparison of Kira LOM to CNC machining.

The JTEC/WTEC panel found many examples where the Japanese are focused on dimensional accuracy and consequently rely on CNC machining over RP approaches. The expected accuracy of the Kira process was noted to be within ±0.1 mm, which is not acceptable for tooling applications. Further, the dimensional accuracy in the stacked layers or z dimension is subject to swelling from humidity, leaving RP with much need for improvement.

INCS

At INCS, a very successful service bureau that is doing very well with its 3D Systems stereolithography apparatus (SLA), a variety of applications are underway (see also Fig. 11.17): rapid tooling via QuickCast (7%); investment casting (15%); vacuum casting silicone and epoxy molds (22%); and design verification (56%). Company representatives indicated they would like to do more in the area of tooling, but they are required to create the computer modeling behind the scenes for a lot of their customers. About 80% of the automotive and electronics companies in Japan use CAD, but they present the CAD model in a 2D form from drawings, not in a 3D model; therefore, essentially the whole modeling effort has to be redone before it can be used for rapid prototyping.

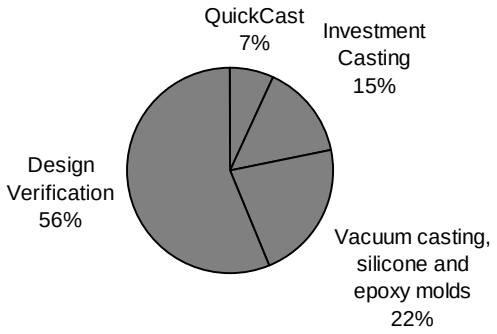


Fig. 11.17. Makeup of rapid prototyping activities at INCS.

INCS has demonstrated the ability to create rapid metal tooling, as in the brass electronic connector shown in Fig. 11.18. Fabricating metal tooling for an electronic connector would normally take about 1.5 months by conventional means, because of the time required to fabricate the pinholes of the connector and the individual pins. A process was used to fabricate multiple insert pins as one assembly by plaster casting a stereolithography QuickCast master pattern.

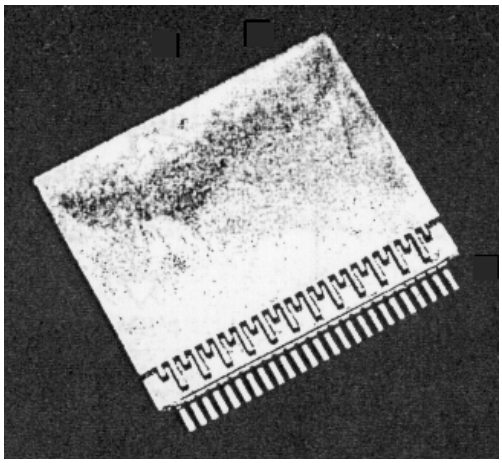


Fig. 11.18. Brass connector made by plaster casting at INCS.

In the method used by INCS (see also the schematic shown in Fig. 11.19), the original 3D model data of an individual insert pin is combined into one assembly of multiple pins using 3D CAD. Then a positive SLA model of the entire assembly is built, which is used as a master pattern to make a negative silicone rubber mold. Another type of silicone rubber is poured into the previously prepared negative rubber mold to form a silicone rubber part of the same positive geometry as the master SLA pattern. A plaster mold is then created around this silicone pattern. The silicone pattern is removed and metal is cast into the cavity. The resulting part has the same geometry as the original SLA pattern. The choice of metal to be ultimately used for fabricating the insert pins depends on the temperature tolerance of the plaster and the required metal tooling strength. For the electrical connector, a high grade of brass was chosen. The desired metal pins are then finally assembled by integrating them into the previously formed connector in one-third the time required by conventional methods.

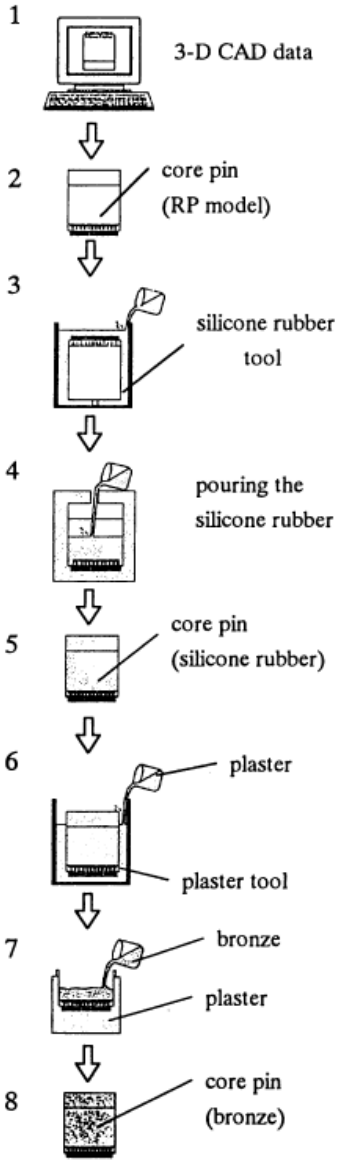


Fig. 11.19. Plaster casting process for rapid metal tooling.

Omron

The JTEC/WTEC panel encountered the RP cultural acceptance issue again at Omron. The Omron representatives expressed their belief that in five years rapid machining will dominate, while rapid prototyping will incrementally advance and continue to be restricted to design use.

Olympus Optical Company

Many camera parts that Olympus makes are very complicated. The company is creating RP models and finishing them to make them look "real." Looking at one of Olympus' RP camera housings or video cameras, it is hard to believe, except when you look on the back side, that it is an RP model, because it is all sanded, painted, and looks very authentic. Panelists did not see any rapid prototype tooling applications per se, but certainly found many examples of functional testing — up to 80% of its applications are tested using stereolithography models. Olympus is eliminating a lot of tooling rework by going this way. That is the flip side of tooling applications: if tooling rework can be avoided, much time, energy, and cost will be saved. Table 11.1 compares resources used to make a camera case by conventional and RP techniques.

Table 11.1
Olympus — Comparison of Resources Used in Making Camera Cases

Process	Number of people required	Days to prepare N/C program or CAD file	Days to machine or make sample	Days to clean up sample	Total days
Conventional Machining	5	10	4	0	14
Stereolithography	2	7	3	1	11

Hino Motors, Ltd.

RP applications at Hino Motors are predominantly in design verification and interference checking. Hino Motors also uses prototypes in engine research and development on the intake side of its engines for short-run functional testing. The company is also finding that it can check design geometry for items such as an instrument panel air vent, in which example there was a significant time savings: checking the vent in the RP sample took 4 hours compared to the usual 2 weeks that would have been required if testing a manually constructed wooden model of the air vent.

Shonan Design Company

Shonan also uses RP primarily for design verification. Its designers have coined the term, "CAM-less" for its injection molds. That is really synonymous with what is going on in Germany, where designers are making the cavity and core of the mold inserts directly, using a computer model and RP. Shonan uses some of the filled resins from Teijin Seiki to produce mold inserts directly using a stereolithography process; however, because the resins have low thermal conductivity, Shonan representatives indicated that they are realizing a 1-2 minute cycle time for part production that used to take seconds. Consequently, they confirmed that research is underway to add conductive fillers in the resin for the mold inserts. There was no direct metal mold activity at Shonan Design Company at the time of the JTEC/WTEC visit.

Japan Aviation Electronics (JAE)

Besides doing functional testing, JAE makes use of rapid prototyping to visualize several of its connector parts. By iterating and using special procedures, such as beam width compensation, thin slice layers, and shrinkage compensation, JAE is finding ways to get the best accuracy from its RP equipment. JAE is able to

attain a dimensional accuracy of ±0.1 mm. The company is realizing a very significant advantage in time and cost savings. Its next step is to model some of its mold core pins to speed mold development.

Toyota

The JTEC/WTEC panelists were unable, because of time constraints and a very structured agenda, to discuss tooling applications with Toyota representatives; however, the panel is aware that there is some work ongoing at Toyota. Toyota representatives did confirm a couple of RP issues that are of concern to them, most of which are identified elsewhere in this study. In addition, Toyota is pursuing studies of birefringence for photoelasticity and development of transparent parts, so designers can look through them to observe colored gasses for evaluation purposes.

SUMMARY

From everything the JTEC/WTEC panel saw in Europe, it is evident that the infrastructure that is being developed in Germany is worth watching, and perhaps something for U.S. universities and industries to get involved in. Panelists were actively invited to participate in the Fraunhofer RP program. With the quality and quantity of the infrastructure that is being put in place, a great deal of R&D can be expected from this program.

In Japan, there remains a broad propensity to compare RP to CNC; however, there are some exceptions. The tooling applications with filled resins underway at Teijin Seiki and Shonan Design certainly represent an approach that is going to mature and eventually catch on. Also, the tooling examples cited at INCS are excellent. To some degree, the Japanese reluctance to quickly change to RP technologies is due to their expert know-how and significant financial investment in numerical control machines: NC works well for them.

Another issue slowing RP acceptance by the Japanese is the relative lack of 3D computer modeling capability. In talking to the attendees at the 1995 Japanese Association of Rapid Prototyping Industry (JARI) conference, this author found the proliferation of 3D CAD in Japan to be very low in comparison to that of the United States (see also Chapter 8). This is a critical issue that Professor Nakagawa brought up when he confirmed that as a country "Japan needs to find ways to get 3D CAD in the workplace." Several Japanese service bureau representatives confirmed that over half of the time they dedicate to RP is in creating 3D CAD models from their customers' 2D drawings.

REFERENCES

Sites. 1996. This reference designates the companion volume to this JTEC/WTEC report: Prinz, F. B., ed. *JTEC/WTEC panel report on rapid prototyping in Europe and Japan.* Vol. II. *Site reports.* Baltimore, MD: Loyola College. NTIS Report #PB96-199583.

SME/RPA. 1996. *Rapid prototyping and manufacturing '96.* Proceedings of the April 23-25 conference, sponsored by the Society of Manufacturing Engineers (SME) and the Rapid Prototyping Association (RPA), held in Dearborn, Michigan.

CHAPTER 12

MEDICAL APPLICATIONS

Allan J. Lightman

INTRODUCTION

Rapid prototyping is having an impact in several areas related to health care. Surgical planning and the fabrication of prostheses have received the greatest prominence, in part due to the dramatic nature of the application. RP systems are key to developing new modalities in other areas of use, such as specialized drug delivery carriers. Surgical applications represent the majority of the activities in Europe and Japan, although there are other applications being pursued.

In the early 1970s, a new mode of X-ray imaging was developed based upon tomographic scanning (computerized tomography, or CT). This modality differs from traditional X-ray shadowgraphy in key aspects, including the fact that linear images are collected along one plane of the object at a time. These images are taken from a variety of angles. The plane of interrogation is then shifted and the process repeated. The information collected for each plane is numerically analyzed to derive the spatial distribution of the X-ray densities within the plane. The information from each plane can then be put together to provide a volumetric image of the structure. Standard CT scanners achieve a resolution of 512 x 512 elements within a layer (1,024 x 1,024 capability is now available in more advanced systems). To scan organs or other regions of interest, the patient is stepped through the measurement plane with a typical pitch of 2-3 mm. Finer scanning of selected regions can be accomplished so long as the total X-ray exposure is kept within safe limits. The numerically reconstructed X-ray density spatial distribution from each "slice" is then printed on X-ray film so that the data presented to the radiologist and/or surgeon is in traditional format (Fig. 12.1).

At about the same time as CT was demonstrated, application of nuclear magnetic resonance (NMR) as an interrogation probe was also demonstrated. The name evolved over the years to magnetic resonance interferometry (MRI) and then finally to MR scanning. MR differs from CT in at least two key aspects: (1) the MR system measures the density of a specific nucleus, and (2) the measurement system is volumetric (interrogation of the entire body, within the measurement volume, is done all at one time). Typically, the MR system is tuned to hydrogen, a common constituent in most soft-tissue cellular matter. It is assumed that this measurement will define the spatial locations of organs by differentiating them according to the densities of hydrogen within their tissues. The system can be tuned to other nuclear species, so long as the nucleus has a magnetic moment (that is, an odd number of protons and/or neutrons). As a result of the diagnostician's familiarity with interpreting CT scan data, MR scan data is also computed and presented in a layer-by-layer format.

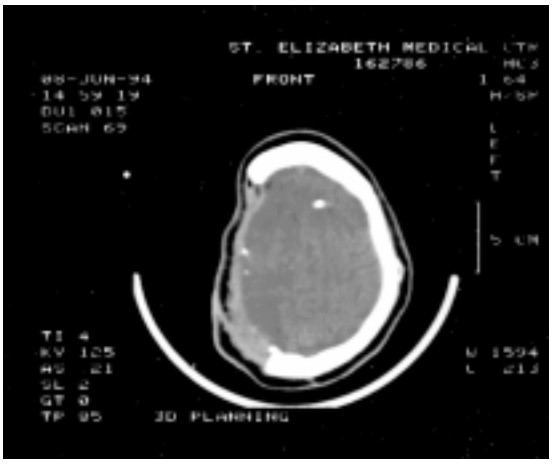


Fig. 12.1. CT section of a skull. X-ray density is mapped to gray scale (University of Dayton).

These two systems, CT and MR, present the finest resolution capability available in diagnostic systems, achieving volumetric resolutions of about 2 mm in each direction. More recently, spiral-scan CT has been developed. In this modality, X-ray data is collected circumferentially as the patient is continuously moved through the scanner. This spiral data collection path provides partial data at every location along the scan. Using interpolation algorithms, a complete scan can be put together at any desired plane, yielding reconstructed slices at considerably finer spacing than stepping systems achieve. The numerical analysis is thought to be more robust, due to availability of the partial data at every plane. Validation tests using phantoms are still underway. Currently, users of spiral-scan CT are claiming isotropic resolution of 0.5 mm or better. Data from other scanning systems (PET, SPECT, etc.) are considerably more coarse. Their output is also presented in a layer-by-layer format.

The information from CT scanner systems provides a host of potential medical applications. Detailed information can be electronically shared among practitioners, thus permitting distributed consultation. This form of telemedicine is providing expert assistance in remote locations. Another application gaining widespread use is the creation of virtual images of the constituents mapped in the images. Full three-dimensional geometry can be assembled from the data. These images can then be formed into stereoscopic presentations viewed from the perspective of a designated platform, providing the equivalent of a "fly-through." These same images, in a static format, can be presented to surgeons during operations, using "heads-up" displays, to guide them (that is, computer-assisted surgery, or CAS). The images are oriented by the use of registration fiducials, located on the patient and visible in the image, and a tracker determining the surgeon's location and view angle relative to the patient. In addition, this layer data format presents a ready path to control current RP systems, which also function on a layer-by-layer basis. This potential transformation was recognized early in RP development, and accurate anatomical RP models were fabricated. This physical realization of CT data has been termed "real virtuality."

These technologies may be able to significantly impact the cost of medical care. Budget demands are placing considerable emphasis on field evaluation. The focus in the United States is on telemedicine and CAS. It is thought that these technologies will have a significant monetary impact. The use of telemedicine is especially important, due to the large physical size of the United States and the difficulty of providing highly trained physicians and surgeons at remote sites. Europe is smaller in size and Japan is much smaller, so issues of distance are less significant there. Telemedicine is still receiving attention, in part due to the application of the same technologies to electronic archiving of patient files. CAS and the application of RP models are under strong development in both regions. There is also a significant effort in Australia in applying RP models for surgical planning. CAS and RP are viewed as complementary, and the RP models offer the advantage of providing stereotactic feedback to the surgeon. Also, the RP models provide a medium for practice efforts; the results can be taken into the surgical theater and used as templates. Furthermore, in

complex reconstructions, models of the desired results are used to provide feedback for the surgeon to gauge how close the actual surgical results approach the planned results.

APPLICATIONS

Data Segregation

The layer data format of scanners quickly prompted the realization that it should be possible to convert the data to be compatible with RP machine requirements. The first task was to separate the data of interest from the general information available from the scanner. Initial efforts focused on CT scan data, and fixed threshold algorithms were used to locate the edge surfaces of bone in each plane. The region-of-interest boundary was located on a pixel-by-pixel basis. Thresholds located within pixels formed “edgels” that were connected into a continuous periphery. Resulting in-plane data showed severe faceting as straight-line edges were used within image pixels. Periphery of the profiles was smoothed by fitting cubic splines or other higher order curves, yielding acceptable in-plane contours (Fig. 12.2).

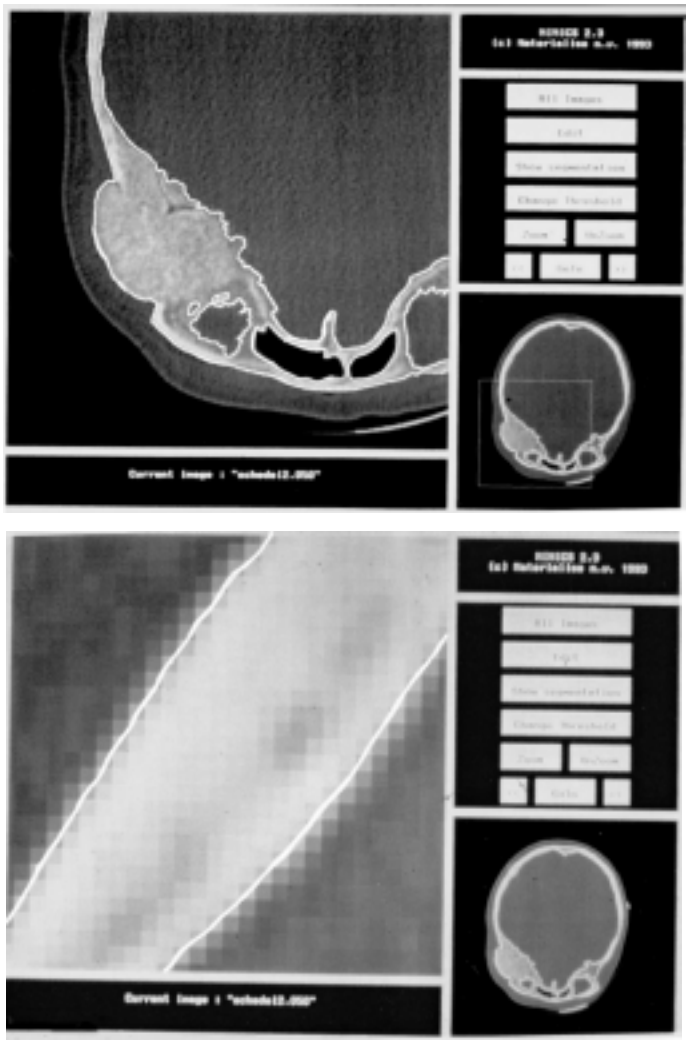


Fig. 12.2. Thresholding results in edgel definition. Connected edgels form bone edge contour. The enlargement shows connection of the pixel edgels (Materialise).

The RP models constructed were based on the coarsely spaced layer data in which a scan layer was repeated on the RP machine until it had built up sufficient material to align with the next scan layer. The resulting structure showed severe staircasing. Overcoming this problem has been a focus of both the European and Japanese programs. Several approaches lead to smoothing of the staircasing. The data between scan layers can be approximated by "morphing" from one layer to the next. Critical transformation locations must be specified. The result will be a smoother profile with a discontinuity at each layer, which can also be smoothed out by fitting splines in the vertical dimension. The results provided data that led to RP models that had excellent appearance and were accurate anatomical models of structures with significant cortical bone, the dense bone structure in the outer areas of heavier bones (Swaelens and Kruth 1993).

Although scan data is typically presented in a two-dimensional format, the film density assigned to a pixel is a measure of the average density measured throughout a volume element (voxel). Consequently, the assigned density associated with the center location of the pixel may actually more closely represent the value at a location on a plane above or below the scan plane. This spatial displacement needs to be taken into account when constructing more accurate models and models with highly figured surface profiles, such as maxillofacial, jaw and tooth, spine, and fine-boned joints of the hand and foot. Another complication that arises in modeling these structures is that when the thickness of the bone structure is smaller than the aperture window for the scanner, the average X-ray density computed for the voxel will be less than the actual bone density, possibly less than the threshold density of the data segregation algorithm. As a result, using fixed threshold data segregation may result in the edgel being located too far into the bone, yielding a measure thinner than the actual bone, or, even more serious, the voxel averaged density may not be sufficient to cross the threshold and a void artifact will be generated.

The medical modeling programs in Europe, Japan, and Australia have concentrated on the application of RP models for diagnostics and surgical planning. Their major effort has been in the development of models for patient-unique structures (as opposed to hip replacements, where a limited set of variations will satisfy all customers). There has been a major focus on maxillofacial and craniofacial reconstruction (Fig. 12.3), jawbone replacement and augmentation, and dental implants. In addition, models of the pelvis, foot, and spine have been examined in some detail. Both the European and Japanese programs recognized the limitations due to the straightforward data interpretation and developed higher order data reduction algorithms that smooth out the surfaces to more closely match the patient's actual geometry. The issue of variable thresholding and void artifacts is a continuing problem. The Australian program is principally focused on surgical applications (Fig. 12.4), mainly relying on European software. In the United States the major thrust of RP modeling has been to hip and knee prosthetics, so current capability has adequately met most needs.

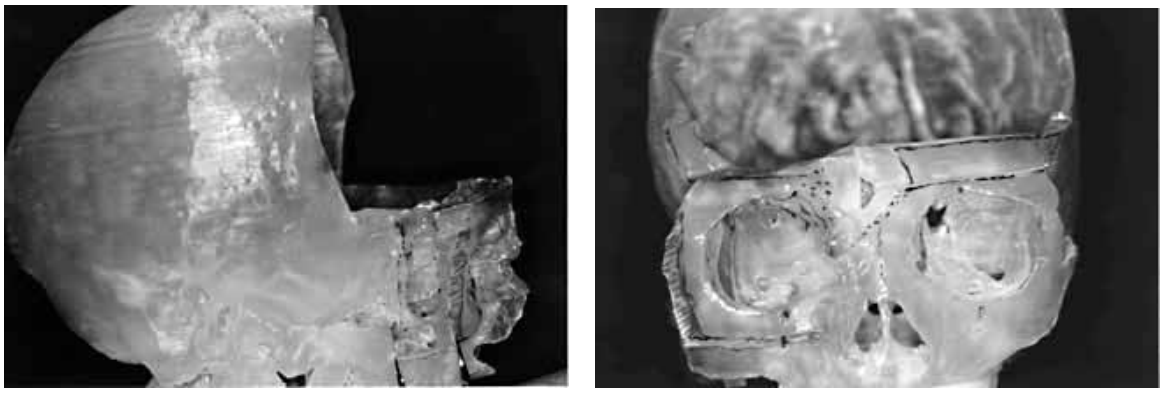


Fig. 12.3. Osteotomy planning of reconstruction for Goldenhar syndrome patient. (Dr. B. Vanassche, Eeuwfeestkliniek, Belgium).

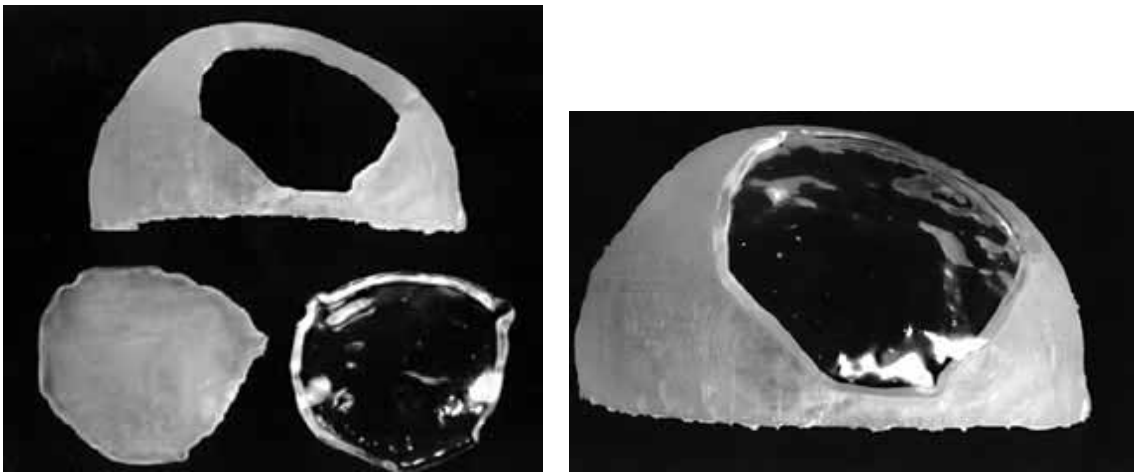


Fig. 12.4. (Left) A cranial trauma was modeled, along with a defect obtained by a Boolean subtraction of the defect from the mirrored, blended opposite face; (right) a biocompatible insert was molded from an RP master and the fit verified before surgical implantation (Dr. P. D'Urso, University of Queensland, Australia).

R&D PROGRAMS

Europe

The most significant effort applying RP to medical modeling, both in number of programs and scope of effort, is in Europe. The major focus is in the BRITE EuRAM PHIDIAS project administered by Materialise, NV (Belgium), an RP service bureau set up in the technology park on the campus of the Catholic University of Leuven. Materialise is developing the CT/MR-to-RP interface software and building the RP models. The project team includes Zeneca Specialties (UK), which is developing new stereolithography resins, and many clinics, hospitals, and university medical research groups.

Other centers focused on surgical applications of RP include: the Institute of Medical Physics at the University of Erlangen-Nürnberg in Erlangen, Germany, where Professor Willi Kalender (developer of the spiral-scan CT) is focused on data interpretation and presentation; the University of Zurich, Switzerland, where Professor Stucki is also studying image analysis and presentation; and the University of Leeds, UK. In addition, there is a significant number of locally funded application evaluations underway throughout Europe, including in France, Austria, Denmark, Italy, and Germany.

The major advances in technology have been made in the PHIDIAS project. These include the development of the software that interprets the CT scan data and generates the files needed to build the models by stereolithography; the development of a two-color resin for stereolithography that permits marking the patient's identification into the model and designating the regions of interest; and a survey quantifying the impact of the model when compared with traditional images.

There is also an RP medical work area specialization that is funded through the European Action on RP (EARP). There is some overlap between the work funded through EARP and PHIDIAS. One project in the EARP program that could have a major impact on the acceptance of RP medical models is the EARP Database Project, which is attempting to quantify the cost-benefit of using RP models in terms of dollars saved, surgical hours saved, enhanced patient service, and speeded recovery. One goal is to be able to justify insurance coverage of the model-making procedure. Another database measuring the effectiveness of RP models has been constructed by Smet (1995) as part of the PHIDIAS project.

The European projects are sufficiently mature to lead to regular conferences focused on the medical applications areas. These include the biannual International Workshop on Rapid Prototyping in Medicine and the annual PHIDIAS Workshop on Stereolithographic Modelling.

Japan

The major program in Japan is focused through INCS, Inc., a Tokyo-based service bureau, and a consortium of six university medical programs. Their main focus is on the creation of models for surgical planning. In addition, INCS is developing software that will provide smoother, more accurate models from the scan data. Its results are not as well publicized as those of the European programs. In addition, there is at least one other project underway, at Hokkaido University, focused on dental implants and tooth repair. INCS has made a cranial implant in ceramic apatite on a multiaxis milling machine. The data was developed using symmetry in the CT-scan data to cover the defect in the skull. The prosthetic was verified by placing it on the RP model of the patient. It was surgically implanted, verifying the accuracy of the procedure. This was done in conjunction with Keio University. Some of the results have been published (Lightman et al. 1995).

Australia

The Australian program is directed by a neurosurgeon, Paul D'Urso, MD, PhD (University of Queensland Department of Surgery, Brisbane), who also has expertise in the engineering and computer aspects of RP. The impressive results illustrate the importance of having surgeons pulling the technology rather than engineers pushing it. Dr. D'Urso's surgical team has used RP models in more than 70 surgeries, and they now rely almost exclusively on the RP models, rather than on the CT scan data, for surgeries where RP models apply. D'Urso uses the Materialise software to convert the scan data for stereolithography model fabrication. His focus has been on the use of the models for both surgical planning (Fig. 12.4) and fabrication of surgical tools.

United States

The major effort in the U.S. programs has been the fabrication of hip and knee replacements. By and large, these units are produced in standard configurations and sizes and stocked as commodity items. There has been limited application of the unique RP models needed for reconstruction surgery and similar applications. There are activities ongoing at centers of research such as the University of Dayton (Ohio); Laserform, Inc. (Michigan), which is working in association with Materialise; Bowling Green State University (Ohio); UCLA; and the Prosthodontics Department of the USAF Medical Center, Lackland AFB. Recently, Materialise opened a U.S. office in Michigan. The U.S. effort is small and there is no central coordination at this time, reflective of the federal government funding being focused almost exclusively on telemedicine and CAS.

OTHER RP APPLICATIONS TO MEDICINE

While the major medical applications of RP technology are related to surgery, there are other applications with the potential to significantly impact health care delivery. (The primary focus of the programs that the panel reviewed outside the United States was surgical applications.) There is an effort in Germany to use laser caving to create a surface structure that will promote bone growth and integration of the prosthesis. In the United States, MIT is studying applications of its Three-Dimensional Printing (3DP) process to the generation of controlled patterned surfaces, which can be applied for prosthesis retention. The capability is also being explored for holding metered amounts of medication in a conveyance that has timed release encapsulation, providing an assured medication supply.

CONCLUSIONS

The use of RP models for surgical planning is making rapid strides outside the United States. Initial results indicate that RP models can provide unique capabilities in specific applications. Programs are principally focused on complex surgeries, where an anatomically accurate model can significantly impact diagnostics, planning, patient counseling, and performance of the procedure. RP models are used where the procedure requires detailed knowledge of the patient's unique anatomical characteristics. Programs in both Europe and Japan are focused on improving the accuracy of the data analysis of the images produced by tomographic scanners. The European program to quantify the benefit of using RP models should provide the concrete statistics needed to present to insurance companies to justify their consideration of this procedure as a covered expense. The U.S. programs are extremely limited. Other medical applications for RP are emerging, and their impact will grow.

REFERENCES

An overview of the global activity can be obtained by studying the subject titles and research sites for the work reported at the biannual International Workshop on Rapid Prototyping in Medicine & Computer-Assisted Surgery, Erlangen, Germany.

Lightman, A. J., B. Vanassche, P. D'Urso, and S. Yamada. 1995. Applications of rapid prototyping to surgical planning: A survey of global activities. In *Proceedings of the Fifth International Conference on Rapid Prototyping*, Dayton, OH.

Materialise. World Wide Web homepage, http://www.materialise.com

Smet, M. H., et al. 1995. Quality requirements and validation of medical models. Paper presented at the 3rd Intl. Workshop on Rapid Prototyping in Medicine & Computer-Assisted Surgery in Erlangen, Germany.

Swaelens, B., and J. P. Kruth. 1993. Medical applications of rapid prototyping techniques. In *Proceedings of the Fourth International Conference on Rapid Prototyping*, Dayton, OH.

APPENDICES

APPENDIX A. PROFESSIONAL EXPERIENCE OF PANEL MEMBERS

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Professor Prinz, the Rodney H. Adams Professor in the School of Engineering and professor in the Departments of Mechanical Engineering and Materials Science Engineering, is also co-chair of Stanford Integrated Manufacturing Association (SIMA). He received his PhD (physics, 1975) from the University of Vienna, Austria, and in 1977 he was awarded a Fulbright-Hays Visiting Fellowship for research at the Massachusetts Institute of Technology. He was professor in the Department of Mechanical Engineering at Carnegie Mellon University (1989-1994), and also Director of the Engineering Design Research Center, a National Science Foundation research center. His current research activities address a wide range of problems related to intelligent design, rapid prototyping, and manufacturing. He has served on the following National Research Council committees: Research Priorities for U.S. Manufacturing, Improving Engineering Design, Joint U.S.-Japan Study Mission on Manufacturing, Opportunities for Computer Aided Decision Support Tools in Materials Selection.

Clinton L. Atwood

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Mr. Atwood is the Rapid Prototyping Team Leader at Sandia National Laboratories, He has worked at Sandia for 20 years (manufacturing). Prior to his work in rapid prototyping he supervised the Heavy Machining Section, Miniature Machining Section, and Machinist Apprentice Section at Sandia. He has been active in the advancement of several rapid prototyping (RP) technologies. Activities include alpha and beta testing of preproduction machines, testing new software and hardware, and participation in technical advisory groups and user groups. He is an active member of the Board of Advisors for the Society of Manufacturing Engineers Rapid Prototyping Association (RPA/SME) and a member of the 1996 RPA/SME conference planning committee. He is the recent past chairman of the North American Stereolithography Users Group. In addition, he participates in the Selective Laser Sintering (SLS) Technical Associates Group at the University of Texas, and in the SLS Users Group. He has authored and presented several papers on the integration and applications of rapid prototyping technologies in manufacturing.

Richard F. Aubin

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Mr. Aubin's 27 years experience at United Technologies Corporation (UTC) included manufacturing assignments in tool and die making, inspection, and numerical control programming. He was responsible for the stereolithography installation at Pratt & Whitney's East Hartford facility. He initiated a group that

supports the rapid prototyping needs of other divisions of UTC. While in this capacity, he initiated beta testing programs of emerging rapid prototyping technologies. He was the coordinator for UTC consortium programs with MIT, Carnegie Mellon University, and the University of Texas. Aubin was a Coordinating Partner in the Intelligent Manufacturing Systems (IMS) Rapid Product Development Program. He authored several publications on rapid prototyping and related topics. Mr. Aubin was a founding member of the Advisory Board for the Rapid Prototyping Association of SME and was on the editorial review board for the *Rapid Prototyping Journal*. He was awarded a BS in Business Management from the University of Hartford.

Joseph J. Beaman

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Professor Joseph J. Beaman joined the UT faculty in 1979 after receiving his doctorate at the Massachusetts Institute of Technology in the Mechanical Engineering Department. Dr. Beaman is presently Director of the Solid Freeform Fabrication Laboratory. He has been coorganizer of the Annual Solid Freeform Fabrication Symposium since the first symposium in 1989. He received the first National Science Foundation Presidential Young Investigator Award in 1984. He has published numerous articles related to his research area. He is also a founder of DTM Corporation, an industrial concern commercializing Selective Laser Sintering. Between January 1988 and October 1991, he was Area Coordinator for the Mechanical Systems and Design Area. He is a member of the Texas Society of Professional Engineers and the American Society of Mechanical Engineers, and has served on the ASME Executive Committee for the Dynamic Systems and Control Division. He was Chairman of this ASME technical division from 1994-1995. He has received numerous grants from both government and private sources.

Robert L. Brown

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Mr. Brown, Director of External Technology for the Gillette Corporate R&D Laboratories, is responsible for identifying and acquiring new technology to support the various product and process lines of Gillette. Besides the blade and razor divisions, other product lines include Braun, AG (personal appliances), Oral-B (oral care products), Stationary Products (including PaperMate, Parker, Liquid Paper and Waterman), and the various toiletries groups. Previously he was Director of Advanced Process and Control R&D and was responsible for developing concepts for high-volume, high-speed manufacturing. He also has engineering management experience in process development for electronic materials and steelmaking at Texas Instruments and Teledyne. He is one of the founders of the Society of Manufacturing Engineers (SME) Rapid Prototyping Association (RPA) and currently serves on the advisory board of RPA. He graduated from Michigan Technological University (BS) in metallurgical engineering and from MIT (SM, ScD) in physical metallurgy. He also has an MBA in accounting and finance from Boston University.

Paul S. Fussell

Affiliation: Senior Technical Specialist, Aluminum Company of America (Alcoa)
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Dr. Fussell is responsible for rapid prototyping at Alcoa. He has been with Alcoa for ten years working on resin-based and metal-spraying rapid prototyping, and on downstream processes for rapid generation of metal tools. He is Alcoa's liaison to university research groups, particularly those at CMU, Stanford, and MIT. He is also a program manager in the area of efficiently relating part measurement data to the desired shape (e.g., the CAD database). Formerly he worked in areas of robot controller design and robotic welding process integration. He received a PhD in Mechanical Engineering from Carnegie Mellon University, writing a thesis entitled "Sprayed Metal Shells for Tooling: Phenomenology, Microstructures, and Properties." He is a member of the honorary organizations Sigma Xi, Tau Beta Pi, and Pi Tau Sigma, and he has authored or co-authored over twenty-eight papers, grants, and patents.

Allan J. Lightman

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Dr. Lightman conducts research and development on technologies and materials for rapid product realization. He cofounded the Rapid Prototype Development Laboratory (RPDL) at the University of Dayton and the annual International Conference on Rapid Prototyping. He is a member of the editorial board of the *International Journal of Rapid Prototyping*, and he was a founding member of the board of the Rapid Prototyping Association of SME. His current RP research focuses on new materials development (ceramics and high-temperature photopolymers) and on applications of RP technology for surgical planning and other medical diagnostics. He reviews RP technology development and implementation worldwide and reports his findings to a variety of industry and government sponsors.

Emanuel Sachs

Affiliation: Associate Professor of Mechanical Engineering, Laboratory for Manufacturing and Productivity, MIT
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Dr. Sachs' specialty is flexible manufacturing, with a primary emphasis on the development of the Three-Dimensional Printing Process, of which he is a coinventor and coprincipal investigator. He is also known for work in the area of Process Control of VLSI fabrication. Prior to joining the faculty, he spent seven years working in the field of photovoltaics (solar cells), two years at Mobil-Tyco Solar Energy Corp, and five years at Arthur D. Little, Inc. He is the inventor of the Edge Stabilized Ribbon Growth method for making low-cost substrates for solar cells. This technology was developed at MIT and Arthur D. Little and is now being commercialized by Evergreen Solar, Inc. of Waltham, MA. Dr. Sachs is the author or coauthor of more than 70 technical papers and is listed as the inventor or coinventor on more than 20 patents. He was awarded the BS (1975), MS (1976), PhD (1983, Mechanical Engineering) from MIT. He was a Hertz Fellow and earned the Hertz Foundation Doctoral Thesis Prize in 1983. Together with coworkers, he was awarded an IR&D 100 award in 1994.

Lee E. Weiss

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Dr. Weiss is a Senior Research Scientist in the Robotics Institute and the Biomedical Engineering Program and is the Director of the Design and Manufacturing Laboratory of the Engineering Design Research Center at Carnegie Mellon University (CMU). He has a bachelor's degree in electrical engineering from the University of Pittsburgh and a master's degree in bioengineering and a PhD degree in electrical and computer engineering from CMU. He was the first graduate student in the Robotics Institute. There he has designed and implemented several systems, including robotic assembly cells, intelligent robot end-effectors, an automated computer vision station for solder joint inspection, an adaptively controlled direct-drive robot arm, a robot leg for a Mars Rover autonomous walking machine, a rapid tool manufacturing system based on thermal spraying, and the Shape Deposition Manufacturing facility. He has 17 patents and is the author of over 50 technical papers.

Michael J. Wozny

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Dr. Wozny has just returned to his professorship at Rensselaer Polytechnic Institute after a leave of absence serving as Senior Advisor to the Undersecretary of Commerce for Technology, dealing with manufacturing competitiveness issues. He established and directed the Design Research Center at Rensselaer for 16 years. He was a laboratory director at National Institute of Standards and Technology (1994-95); senior fellow at Industrial Technology Institute (1991); a division director at the National Science Foundation (1986-88); and researcher at General Motors Research Laboratory (1972). He established, helped plan, and participated in the U.S.-Japan Technical Exchange Forums in Manufacturing (1988, 1990), coordinated by the National Research Council. He has worked in computer graphics, computer-aided design, rapid prototyping and manufacturing. He is chairman of the International Federation for Information Processing (IFIP) working group 5.2 (CAD), and he has received the IEEE Centennial Medal (1984), and the National Computer Graphics Association Academic Award (1988).

APPENDIX B. PROFESSIONAL EXPERIENCE OF OTHER TEAM MEMBERS

Kesh Narayanan

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Dr. Narayanan is currently the program director overseeing research interests in the area of machines and manufacturing processes at NSF. He is charged with the identification of leading edge technologies and encouraging innovative research ideas in materials processing. Prior to coming to NSF in 1994, he was the Chief Scientist at Certainteed, a building materials company. His duties included leveraging research results from the academic world and applying them to the business. His longest tenure was at Norton Company, spanning 20 years. As the R&D Director of Norton Abrasives Business, he led the worldwide introduction of new products with a track record of new products accounting for more than 25% of total sales. Innovations included new materials such as seeded sol-gel Alumina, novel polymer compositions for bonding of abrasives, introduction of high-speed cut-off wheels, and many more covering the area of manufacture and use of grinding wheels. His department is credited with over 30 patents. He received his PhD (Materials Science and Engineering) from Carnegie Mellon University in 1974 and his BS from the Indian Institute of Technology.

Robert Duane Shelton

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Dr. Shelton received his degrees in electrical engineering from Texas Tech, MIT, and the University of Houston. He has been a professor at the University of Houston and Texas Tech, and at the University of Louisville, where he was Chairman of the Applied Math and Computer Science Department. He has also worked as an engineer at Texas Instruments, at NASA on the Apollo space communications system, and at the National Science Foundation as a science policy analyst. He has served as principal investigator on over 25 grants and contracts totaling over $2 million. He is presently professor of engineering and computer science at Loyola College in Maryland. He is also Director of the International Technology Research Institute at Loyola, which assesses foreign technologies on behalf of the National Science Foundation, NASA, the Department of Energy, DARPA, ONR and the Department of Commerce.

Cecil H. Uyehara

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Cecil H. Uyehara is a consultant in the Washington DC area on U.S.-Japanese relations in science and technology fields. He served in the U.S. government for almost 25 years, with the Air Force (weapons systems planning), the Office of Management and Budget (military assistance) and the Agency for International Development (AID). He has published books and articles on Japanese politics, scientific advice and public policy, Japanese calligraphy, and Afghan philately. He organized the first U.S. Congressional hearings on Japanese science and technology, lectured at the U.S. Foreign Service Institute on Japanese science and technology, and served as a consultant to the *Yomiuri Shimbun* and the Library of Congress on

Japanese calligraphy. He graduated from Keio University (BA), the University of Minnesota (MA), both in political economy, and received awards/grants from the Ford Foundation, American Philosophical Society, University of Minnesota (Shevlin Fellowship) and the National Institute of Public Affairs (Fellowship at Harvard University, 1963-4).

APPENDIX C. PARTIAL LISTING OF WORLD WIDE WEB HOMEPAGES FOR SITES VISITED BY THE PANEL (See also Chapters 7 and 8 for other relevant WWW homepages)

Bavarian Laser Center (BLZ)
http://faufthp7.lft.uni-erlangen.de:8080/

Catholic University of Leuven, Division of Production Engineering, Machine Design, and Automation (PMA)
Home page: http://www.mech.kuleuven.ac.be/pma/pma.html
Rapid prototyping: http://www.mech.kuleuven.ac.be/pma/research/95/2_2/htm

Materialise
U.S. site (info. limited to Materialise software): http://www. materialise.com/
European site (info. on all RP activities): http://www.materialise.be/

Fraunhofer Institute for Applied Materials Research (IFAM)
http://www.ifam.fhg.de

Fraunhofer Institute for Manufacturing Engineering and Automation (IPA)
http://www.ipa.fhg.de

University of Stuttgart, Institute for Polymer Testing and Polymer Science (IKP)
http://www.ikp.uni-stuttgart.de

University of Tokyo, Prof. Kimura
http://www.cim.pe.u-tokyo.ac.jp/index-j.html

APPENDIX D. GLOSSARY

3DP	Three-dimensional Printing (MIT)
AFPR	Association Française de Protypage Rapide (France)
AI	Artificial intelligence
AOM	Acousto-optic modulator
AP	Application protocol
ASA	Acrylnitril styrene acrylic copolymer
BIBA	Bremen Institute for Industrial Technology and Applied Work Science (EU project)
BPM	Ballistic Particle Manufacturing (process and U.S. company)
BRITE EuRAM	Basic Research of Industrial Technologies for Europe, European Research on Advanced Materials program
CAD	Computer-assisted design
CAE	Computer-assisted engineering
CALS	Commerce at Light Speed (Japanese R&D program)
CAM	Computer-assisted manufacturing/machining
CAS	Computer-assisted surgery
CAT	Computed axial tomography
CBN	Cubic boron nitride
CLI	Common layer interface (format alternative to STL)
CMM	Coordinate measurement machine
CNC	Computer numerical control
CT	Computed tomography (medical)
DFE	Data Front End, a Cubital software package
DMEC	Design Model Engineering Center (Japan)
DSPC	Direct Shell Production Casting
DTM	A U.S. Corporation based in Austin, TX
DTM	Desktop manufacturing
EARP	European Action on Rapid Prototyping
ECM	Electrochemical machining
ECU	European Currency Unit
EDI	Electronic data interchange
EDM	Electrical discharge machining
EFTP	Euro File Transfer Protocol (for arbitrary partners)
EMI	Electromagnetic interference
EOS	Electro-Optical Systems (Germany)
EU	European Union
FDM	Fused Deposition Modeling (Stratasys)
FEA	Finite element analysis
FEM	Finite element mesh
FhG	Fraunhofer Institute
HPGL	Hewlett-Packard Graphics Language

I-DEAS	CAD software from SDRC in Milford, OH
IFSW	Institute for Laser Technology (Stuttgart)
IGES	Initial graphics exchange specification
IMS	Intelligent manufacturing system
IP	Intellectual property
IPR	Intellectual property rights
IROFA	International Robotics and Factory Automation Center
ISDN	Integrated services digital network
ISO	International Standards Organization
JARI	Japan Association of Rapid Prototyping Industries
JSR	Japan Synthetic Rubber
LAN	Local area network
LANL	Los Alamos National Laboratory
LEAF	Layer-exchange ASCII format
LOM	Laminated Object Manufacturing, trademark of Helisys (LOM-2030™)
LSI	Large-scale integrated circuits
MAGICS	Software, registered trademark of Materialise N.V.
MJS	Multiphase jet solidification (IFAM/IPA)
MRI	Magnetic resonance interferometry
NC	Numeric control (machining/milling)
NMR	Nuclear magnetic resonance (MRI or MR now used)
NURBS	Nonuniform rational B-spline
ODETTE [OFTP]	File transfer protocol for automotive industry and suppliers
pcb	Printed circuit board
PCC	Precision Castparts Corporation (France)
PEEK	One of several super engineering plastics
PS	Polystyrene
QFD	Quality function deployment
RIM	Reaction injection molding
RP	Rapid prototyping
SAHP	Selective Adhesive and Hot Press Process (Kira)
SCS	Solid Creation System (Sony)
SDM	Shape deposition modeling/manufacturing
SFF	Solid freeform fabrication
SGC	Solid ground curing (Cubital)
SHG	Second harmonic generation
SL	Stereolithography
SLA	Stereolithography Apparatus (3D Systems)
SLP	Solid laser plotter
SLS	Selective laser sintering (DTM Corp.)
SME	Society of Manufacturing Engineers
SOUP	Solid Object Ultraviolet (laser) Plotter (CMET)
SPL	Stereophotolithography

staircasing	RP edge effect description
STEP	Standard for the exchange of product model data
STL	A computer model (CAD) file format that is rendered in triangular facets. Also called a tessellated file. [Stereolithography Text Language]
TPM	An RP cleaning solution
VR	Virtual reality
VRML	Virtual reality modeling language
WAN	Wide area network
WWW	Worldwide web
WZL	Machine Tool Institute of Aachen, Germany

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