Overview of the WTEC Additive/Subtractive Manufacturing Study of European Research

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ABSTRACT

As a follow-up to the 1996 JTEC/WTEC study of rapid prototyping research in Europe and Japan, the 2003 Additive/Subtractive Manufacturing study assessed the evolution of RP technologies and new developments in the area. The goal of this study was to gather information on the worldwide status and trends in additive/subtractive (A/S) manufacturing science and technology and disseminate it to government decision makers and the research community. This talk will present the primary observations, results, and conclusions of the study. Highlights include: The European Union has an organized effort to make advances in A/S manufacturing, the levels of activity and infrastructure are superior to the US, and European countries have targeted rapid manufacturing - the science and technology of production manufacture using A/S technologies. The talk also provides the context for subsequent presentations in the Session on European SFF Programs.

Keywords: Advances in RP Applications, Innovative RP Applications, Rapid Manufacturing, Additive/Subtractive Manufacturing, Advances in Materials.

SCOPE OF STUDY

Additive/Subtractive (A/S) manufacturing as defined in this paper encompasses Additive Manufacturing techniques, sometimes labeled as Solid Freeform Fabrication (SFF), as well as technologies that combine additive and machining (subtractive) operations. We wish to study SFF techniques in combination with integrative approaches to material synthesis and manufacturing. SFF technologies are capable of producing complex freeform solid objects directly from a computer model without part-specific tooling or knowledge (Jacobs, 1992, Beaman et al 1997, Venuvinod and Ma, 2004). These techniques have been developed over the last 20 years and are well established in the area of rapid prototyping of mechanical elements. The complexity that can be obtained from SFF parts is impressive. This complexity comes at a very low cost as compared to other manufacturing processes such as machining. SFF processes are just starting to emerge as true manufacturing processes for mass customized products. If these processes can be used effectively for true manufacturing rather than just prototyping, A/S manufacturing holds the promise of drastically decreasing the time to market for new products and reducing the life cycle costs of existing products. In this study, research and development program in Europe are assessed and compared with efforts in the United States.

This initiative was sponsored by the U.S. government and administered by World Technology Evaluation Center (WTEC) at Loyola College in Maryland. The following agencies supported the study: National Science Foundation, Defense Advanced Research Projects Agency, Office of Naval Research, and the Department of Commerce. The outcome of this report is based primarily on observations during the site visits but other input from the panel is also included. The panel visited 15 sites in 5 European countries with two to three members in each group. The sites visited were primarily academic or research institutes and development companies.

The annual worldwide market for these systems is approximately $500 million. There are approximately 10,000 machines installed worldwide and the US has approximately 40% of these systems (Wohlers, 2003). Direct manufacturing only represents 3.9% of present utilization, but this is the area of most potential for growth in the technology. An example of this potential is provided by Boeing Corporation. With a spin-off company, On-Demand Manufacturing, Boeing produces ducting using Selective Laser Sintering machines and installs this directly in fighter aircraft. With this procedure, they can drastically reduce part count. Other examples include hearing aid shells being made by Siemens, Phonak, and Widex, and the Invisalign® orthodontia system marketed by Align Technology.

It is in this area that we focused our study. In particular, we looked at processes appropriate for the custom manufacture of products, not just models. Other areas of particular interest to the panelists and the sponsors were applications in medicine and tissue engineering, materials synthesis enabled by and developed for these processes, environmental impacts and benefits, and energy applications.

It is clear from our site visits that the European community has recognized the potential of this technology for manufacturing. They are backing this up with considerable investment for research and development infrastructure and support.

METHODOLOGY

A pre-visit workshop was held in Washington in the Spring of 2003 with prospective panel members and representatives from the sponsoring agencies in order to decide on the scope of the study. The expert panel was selected by recommendations from the study chairman and representatives of the sponsoring agencies. This paper and the final report are based primarily on observations during the site visits but other input from the panel is also included. The panel visited 15 sites in 5 European countries with two to three members in each group. The sites visited were primarily academic or research institutes and development companies. In December 2003, a public workshop was held at the National Science Foundation to disseminate study results. All site reports will be made available on the web (http://www.wtec.org/additive) in 2004. Site visit reports were reviewed by the host organizations prior to publication.

Panel Members

The following experts served as panel members for this study.

- Clint Atwood, Sandia National Laboratories
- Joe Beaman (panel chair), University of Texas at Austin
- Ted Bergman, University of Connecticut
- Dave Bourell. University of Texas at Austin
- Scott Hollister, University of Michigan
- David Rosen, Georgia Institute of Technology

Several sponsor representatives traveled with the panel, including:

- Khershed Cooper, Office of Naval Research
- George Hazelrigg, National Science Foundation
- Kevin Lyons, National Institute of Standards and Technology
- Hassan Ali, WTEC.

In addition Fritz Prinz, Stanford University, served as a Senior Advisor to the study.

Sites visited

The group visited sites in Europe during October 20-24 and October 1-4; see Table 1.

Table 1: Sites visited.

Country	Site	Panelists	Date
Germany	Fraunhofer Institute for Manufacturing and Advanced Materials (IFAM)	Bourell, Bergman, Cooper, Ali	Oct. 20, 2003
	University of Bremen, BIBA	Bergman, Bourell, Cooper, Ali	Oct. 20, 2003
	Freiburg Materials Research Center	Hollister, Bourell, Bergman, Cooper, Ali	Oct. 21, 2003
	Fraunhofer Institute for Laser Technology (ILT)	Bourell, Hollister, Cooper, Ali	Oct. 22, 2003
	Fraunhofer Institute for Production Technology (IPT)	Bourell, Hollister, Cooper, Ali	Oct. 22, 2003
Finland	Helsinki University of Technology	Atwood, Beaman, Hazelrigg	Oct. 24, 2004
Sweden	IVF Industrial Research and Development Corporation	Beaman, Atwood, Hazelrigg	Oct. 23, 2003
The Netherlands	TNO Industries	Bourell, Hollister, Cooper, Ali	Oct. 23, 2003
Portugal	Polytechnic Institute of Leiria, Portugal	Bourell, Rosen	Oct. 1-4, 2003
UK	Imperial College	Hollister, Atwood, Beaman, Rosen, Hazelrigg, Lyons	Oct. 20, 2003
	Loughborough University	Atwood, Beaman, Rosen, Lyons, Hazelrigg	Oct. 21, 2003
	University of Nottingham	Rosen, Atwood, Beaman, Hazelrigg, Lyons	Oct. 21, 2003
	Manchester Materials Science Center	Rosen, Atwood, Beaman, Bergman, Hazelrigg, Lyons	Oct. 22, 2003
	University of Liverpool	Bergman, Rosen, Lyons	Oct. 23, 2003
	University of Leeds	Bergman, Rosen, Lyons	Oct. 24, 2003

SITE VISIT HIGHLIGHTS

Early on in the course of the study it became evident that SFF manufacturing technology development was a priority at most of the sites visited and that teaming relationships were established between universities, industry, and government entities within each country and in many cases across Europe. This paradigm was validated during a review of site reports from each of our teams. The majority of the SFF research and development in Europe was focused on advanced development of existing SFF technologies by improving processing performance, materials, modeling and simulation tools, and design tools to enable the transition from prototyping to manufacturing of end use parts. Additionally, there were several efforts in applications development for limited production parts and studies were underway to compare SFF techniques with traditional manufacturing processes.

In Germany, the Fraunhofer Institutes and the University of Freiburg have major SFF manufacturing initiatives. At the Fraunhofer ILT (Aachen), there is work in direct metal laser fabrication. They developed a LENS-type direct metal machine and produced a variety molds in a wide range of metals, as well as industrial parts for aerospace applications (Ti and superalloys). They developed the Selective Laser Melting (SLM) process, a variation of SLS that can produce fully dense parts (see Fig. 1). A commercial version of a SLM machine was showcased by TRUMPF at the Euromold Conference in December 2003. Fraunhofer IPT (Aachen) works on combining layered manufacturing with subtractive machining is ongoing. Controlled Metal Build-Up (CMB) is a LENS-type process with a machining step after each layer build. Both powder and wire feeds are used. High-speed 3-axis milling is performed after each build step.

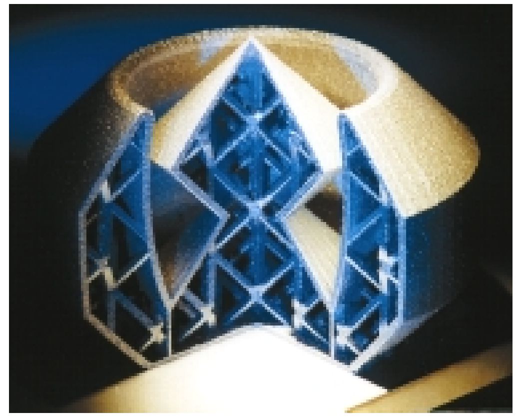

Fig. 1: Complex part from SLM. (courtesy Fraunhofer ILT)

At the University of Freiburg, the interest of the Materials and Technology division is in (1) polymer design, (2) design of hybrid materials, (3) reactive processing, (4) nanotechnology, (5) characterization, (6) tissue engineering and (7) dental materials, and (8) rapid manufacturing. A new rapid manufacturing technology known as the 3D Bioplotter was developed initially by the Freiburg Materials Research Center (FMF) and a commercial version was later developed by Envisiontec (www.envisiontec.de) in conjunction with FMF, as shown in Fig. 2. The 3D Bioplotter also has the unique capability among commercial machines to plot live, viable biological cells within a hydrogel. Additionally, tissue engineering scaffolds can be fabricated with a number of materials.

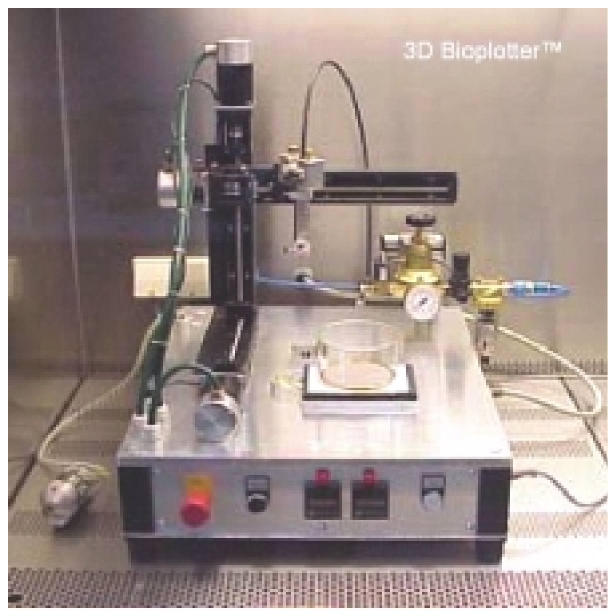

Fig. 2: Bioplotter from EnvisionTec.

In the United Kingdom, the University of Loughborough's Innovative Manufacturing Research Center (IMRC) has a budget of $24M over five years. Their Rapid Manufacturing Research Group has a budget of $1.25M per year (guaranteed for 5 years) and covers 35 staff and PhD students. They had several projects directed at the development and evaluation of A/S technologies for production manufacture, including customized soccer shoes, and even textiles. They also had projects focused on analyzing and improving SFF technologies, including SLS, ultrasonic consolidation (Solidica's process), and the Contour Crafting process from USC. Their facilities and equipment were very impressive.

There are also major research efforts at the University of Manchester Institute of Science and Technology. The Manchester Materials Science Center has a large program on ink-jet printing of polymer and ceramic materials. They are investigating jetting technologies for viscous slurries containing up to 50 percent by volume ceramic powders. At the Laser Processing Research Center, a large research program is investigating a wide range of additive manufacturing processes, including direct metal deposition (LENS-like process), SLS processes and materials, and a new laser-based electrodeposition process for metals.

The University of Liverpool has a major program in laser processing of materials. Fundamental research is being performed in their College of Engineering, while industrial focused R&D activities are centered within the Lairdside Laser Engineering Centre. The Centre includes industrial CO_2 lasers with up to 3.5kW beam powers and 6-axes manipulation, as well as industrial Nd:YAG lasers from 500W to 4kW beam power and 7-axes manipulation. They developed a LENS-like machine and have fabricated parts in fully dense titanium alloys and graded materials. Within their Mechanical Engineering Department, they were pursuing new applications enabled by the shape complexity capabilities of SFF processes, including micro heat exchangers and biomedical implants.

The University of Nottingham has two research centers that have significant SFF activities, the Rolls Royce University Technology Center and the Univ. of Nottingham Institute for Materials Technology (UNIMAT). Rolls Royce has an aircraft engine manufacturing facility near Nottingham and they provide core funding for UTC. One major project is the usage of laser cladding processes for engine blade repair. An example of their work is shown in Fig. 3. Within UNIMAT, they have major efforts in laser welding/cladding, cold spray of metals, thermal spray, and laminated tooling.

Fig. 3: Turbine blades with laser cladding build-up. (courtesy Nabil Gindy, Univ. of Nottingham)

Research at the University of Leeds includes extensive physical modeling and experimentation directed to the understanding and prediction of the thermo-mechanical response of various materials to laser irradiation, specifically for SLS processes. Several biomechanical applications include the SLS of bioactive glass ceramics with bio-polymer infiltrants, utilization of SLS for pre-surgical planning, SLS of bone replacement materials, and mass customization of orthoses for sufferers of arthritis. A project was starting on the environmental and economic benefits of conformal cooling channels in injection molds.

In Sweden, the IVF Industrial Research and Development Corporation assists companies with research and development. Considerable A/S manufacturing activity is occurring in this region around Gothenburg, which includes Chalmers Institute of Technology. Arcam developed a new method for direct metal fabrication that uses an electron beam rather than a laser to selectively melt portions of a powder bed layer, similar in nature to SLS. A schematic of their process is illustrated in Fig. 4. They have made fully dense parts out of Ti6-4, commercially pure Ti, low alloy steels, tool steel, nickel alloys, and iron. The company SpeedPart is working on a machine that uses a mask to irradiate an entire layer and melt the unmasked portions of a powder bed. This should enable high speed fabrication. The company fcubic is also pursuing a high speed fabrication, but using ink-jetting technology. Other organizations are working on methods of processing ceramics and for improving EOS SLS machines and materials.

Finland also has considerable activity. The Helsinki University of Technology has four major programs related to advanced manufacturing development. They include: Rapid Prototyping and Manufacturing (RP&M) Applications Development; Product Development for Rapid Manufacturing; Rapid Manufacturing Logistics and Business Concepts Research; and Sheet Metal Rapid Manufacturing Research. At HUT, a major emphasis is on rapid manufacturing applications of laser sintering. They have improved the EOS Direct Metal Laser Sintering process. They showed many high quality metal parts and tools that they and Finnish companies have fabricated. As part of their education program, they utilize SFF parts in tooling and casting applications. A unique development project at HUT is the use and characterization of an off-the-shelf machine, from Amino Corporation in Japan, for fabricating prototype sheet metal parts. A sheet metal blank is shaped by a round stylus to form the sheet into the desired shape.

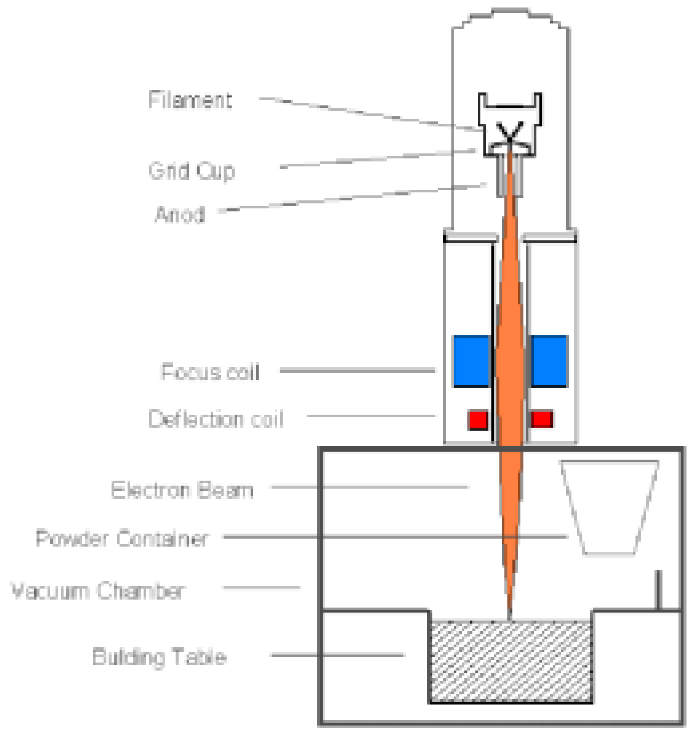

Fig. 4: Arcam EBM schematic.

In the Netherlands, TNO Industrial Technology in Eindhoven is part of the TNO, a non-profit, non-government organization focused on R&D and as the interface between university basic research and business applications and commercialization. They have an EOS SLS machine, a Stratasys FDM machine, two home-built inkjet machines, a home-built FDM machine, and recently acquired an Envisiontec Perfactory machine. Many research projects were focused on rapid manufacturing and customization. Biomedical implants and dental restorations were being investigated. They had an ambitious program to develop ink-jetting capabilities for ceramic slurries, similar in objectives to the UMIST effort. They also have a large program in materials development for SFF and other manufacturing processes.

ASSESSMENT OF EUROPEAN ACTIVITY

The European Union has an organized effort to make advances in SFF

The European countries have just finished a coordinated program entitled RAPTIA (www.raptia.org). RAPTIA is the name of a European thematic network of research organizations, universities and industries working with Rapid Tooling. The network was funded by the European Commission, and was started in 1999. Project organizer was TNO in the

Netherlands. The project finished in 2003 and will likely be followed by a new program, Network of Excellence in Rapid Manufacturing (NEXTRAMA), funded by the European Union's sixth Framework Program (FP6). Its mission is to drive the growth of rapid manufacturing (based on additive freeform fabrication technologies) to efficient and sustainable industrial processes. This will occur by integrating and coordinating the main scientific, technological, industrial, and social elements in Europe by creating a permanent organization in the field of rapid manufacturing. To fulfill this mission, a concerted effort will be planned, executed, and monitored by specific research units. The resulting exploratory work, knowledge, facilities, and experience sharing will provide a clear definition of the primary development themes and related research teams required to follow specific roadmaps, leading to viable industrial solutions. NEXTRAMA is planned to have a 7-year duration. Funding levels of over $1.68m per year will provide funds for organization and management of the project. Individual research activities will receive additional funding or will be funded by other government or industry programs.

All individual European countries visited are investing in SFF technology. The combined level of activity and infrastructure is superior to the U.S. In the United Kingdom, the Engineering and Physical Sciences Research Council and industry are providing significant funding for programs. In Sweden, there is government and industrial support for SFF technology development through semi-public research institutes. In Finland, TEKES and industry are providing support for universities and industry. In Germany, the Fraunhofer Institutes, industry and government are supporting numerous programs. In the Netherlands, the TNO structure is providing support to programs.

European countries have targeted Rapid Manufacturing

As mentioned in the Site Visit Highlights section, individual countries have significant efforts underway to assist their companies in achieving rapid manufacturing. This is illustrated well by the timeline established by the Swedish company ***fcubic*** for the adoption of rapid manufacturing:

Generation 1: 1986 - 2002: Up to 100 parts, prototypes and models.

Generation 2: 2000 - 2008: Short series production 1 to 10,000 small and complex parts.

Generation 3: 2006 - 2012: Medium series production 1 to 1,000,000 items.

Research and Development. There are several points to be made concerning the status of research and development of rapid manufacturing in Europe.

1. There is substantial funding for important process development of SFF technologies that were in many cases initiated in the US (laser sintering of powders, direct metal deposition and laser fusion of powders, and ink jet printing techniques).
2. Total R&D activity in SFF is presently higher in Europe than in the U.S.
3. As compared to the 1995 study, there is more innovative and leading edge R&D going on in Europe. Examples of this are the ARCAM e-beam development and the Envisiontec Bioplotter.
4. As compared to the U.S., there is much closer tie between university research and industrial needs, but basic science is still present in the research.

5. There are a limited number of truly integrated layer by layer additive/subtractive processes under development. There is work in Germany at IPT on Control Metal Buildup that combines laser deposition with machining and at Concept Laser GmBH on combining laser sintering, laser marking, and laser machining. Instead European emphasis is on opportunities in rapid manufacturing not on any one process. They are interested in the entire process chain to create new business models. Customers want function and new SFF capabilities lead to new applications such as dental implants and hearing aid shells.
6. The combined work of Freiburg/Envisiontec for tissue scaffolding is as or more advanced than any worldwide. The commercially available 3D Bioplotter is the first biospecific fabrication system that can print the entire range of biomaterials *and cells* that will be the future of biofabrication.
7. There is no work in fabricating fuel cells with SFF but the possibility is innovative and of interest.
8. European researchers recognize the need to consider the environmental impact of A/S processes, particularly as more production manufacturing application emerge. Research underway in this area at present is limited.
9. Many hosts mentioned the inadequacies of existing CAD for design of parts to be fabricated by SFF. There is a keen recognition of the need for user friendly software.
10. As in the U.S., the number of rapid prototyping service bureaus has declined. Many companies are obtaining concept modelers for rapid prototyping, which is a separate market from rapid manufacturing.
11. Most European researchers would welcome collaboration on international programs/projects with U.S. researchers.

China Assessment. Although the panel did not visit China for this report, there was significant mention of the effort that is being initiated in China. Two sites in China were of significance. Tsinghua University has a large Research Group in SFF under the direction of Professor Yan. This group is associated with Beijing Yinhua company. They are developing an extrusion based system, a laminated object system, a sand system, and a tissue scaffold system The China National Machinery Import & Export Corp is their sales agent. Huazhong University of Science and Technology has 120 Researchers in SFF. They are the largest single group in the world on one site. They are associated with Wuhan Binhu Corporation and are developing selective laser sintering, laminated object manufacturing, and stereolithography.

FUTURE REQUIREMENTS AND BARRIERS

In this section, we develop a necessary set of requirements for successful rapid part manufacturing. Also included are brief requirements for biological prototyping and manufacture and fuel cell prototyping and manufacture.

Requirements for Rapid Part Manufacture

- Design tools for SFF. Present computer solid modeling design tools focus on features (holes, slots, etc that are to be machined) that have little or no significance to SFF processes. Entirely new CAD design tools need to be developed that aid the designer to exploit the capabilities of SFF.

- Speed. The fastest SFF systems cannot compete with high volume production processes like injection molding or die casting once molds are made. But, even with today's SFF systems, there are applications that make economic sense. Examples are Align Technology's orthodontic product, Siemen's hearing aid shells, and On Demand Manufacturing's aerospace parts for Boeing. These applications are relatively low volume, complex, customized parts. Speed needs improvement to broaden production opportunities.
- Post processing and finishing. Presently, most SFF parts require hand finishing in order to meet product specifications especially surface finish. Hand finishing is not a good option for production applications because of cycle time and product variability. The process chain needs to be automated and integrated to eliminate hand processing.
- Accuracy and Repeatability. Present systems can not achieve the standards of performance required for many production applications. Systems need to reliably produce +/- 0.125 mm accuracy or better.
- Standards. With the exception of the STL file format, the SFF industry is far from being standardized. The lack of standards inhibits growth especially in production applications. Market driven standards need to emerge.
- Cost and size. Along with cycle time, production costs and working envelope are critical when choosing a manufacturing process. Cost will naturally come down based on installed base of systems but further improvement is needed. System costs and working envelope need to be comparable to machining equipment.
- Green Manufacturing. As production becomes more prevalent, environmental issues will become increasingly important. These issues include material usage (recycling unused powders), energy costs, and total life cycle product costs. Systems need to be designed for environmental concerns and total life cycle product costs.
- Materials. New manufacturing applications are enabled by new materials. The choice of materials in the present systems is limited and their properties are not usually predictable nor stable. SFF-specific materials need to be developed for specific systems and applications.

Requirements for Biological Prototyping and Manufacturing

Requirements for biological prototyping and manufacturing are:

- Multiple material system ranging from ceramics, polymers, to hydrogels,
- Processing of human body-like environment to enable printing living cells, genes, and proteins,
- Features on the order of microns, control of nanoscale structure for diffusion barriers
- Information technology for handling of biological and communication data.

Requirements for Fuel Cell Prototyping and Manufacturing

Requirements for fuel cell prototyping and manufacturing are:

- The ability to fabricate complex microstructure as well as complex geometry,
- Precision multiple material processes on the scale of a micron,
- The ability to control porosity,
- The ability to design and build pathways for efficient material and energy flows in the cell,
- The integration of multiple process steps for efficient manufacturing.

Following WTEC tradition, the panel created a chart to rank the relative strengths and trends in A/S Manufacturing in Europe and the United States. The result is shown in Table 2.

Table 2: Comparison of U.S. and European R&D in ƒƒƒ ±d*manufacturing*

Categories	**Global Knowledge Base**	**Europe Compared to U.S.**	**Perceived European Future (5-10 yrs) Relative to U.S.**
Processes	HIGH	Caught Up	⇑
Manufacturing	MED	On par w/isolated superiority	⇑
Materials & Materials Processing	HIGH	Comparable	⇔
Biological Applications	LOW	On par w/isolated superiority	⇔
Controls	HIGH	Lagging	⇔
Energy	VERY LOW	Limited	⇓
Environment	LOW	Leading	⇑
Infrastructure/Equipment	-	Clearly Superior	??
Funding	-	Clearly Superior	??

⇑ = better than U.S. ⇔ = on par with U.S. ⇓ = lower than U.S.

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