History of additive manufacturing

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This 26-page document is a part of *Wohlers Report 2012* and was created for its readers. The document chronicles the history of additive manufacturing (AM) and 3D printing, beginning with the initial commercialization of stereolithography in 1987 to May 2011. Developments from May 2011 to May 2012 are available in the complete 287-page version of the report. An analysis of AM, from the earliest inventions in the 1960s to the 1990s, is included in the final several pages of this document.

Additive manufacturing first emerged in 1987 with stereolithography (SL) from 3D Systems, a process that solidifies thin layers of ultraviolet (UV) light-sensitive liquid polymer using a laser. The SLA-1, the first commercially available AM system in the world, was the precursor of the once popular SLA 250 machine. (SLA stands for StereoLithography Apparatus.) The Viper SLA product from 3D Systems replaced the SLA 250 many years ago.

In 1988, 3D Systems and Ciba-Geigy partnered in SL materials development and commercialized the first-generation acrylate resins. DuPont's Somos stereolithography machine and materials were developed the same year. Loctite also entered the SL resin business in the late 1980s, but remained in the industry only until 1993.

After 3D Systems commercialized SL in the U.S., Japan's NTT Data CMET and Sony/D-MEC commercialized versions of stereolithography in 1988 and 1989, respectively. NTT Data CMET (now a part of Teijin Seiki, a subsidiary of Nabtesco) called its system Solid Object Ultraviolet Plotter (SOUP), while Sony/D-MEC (now D-MEC) called its product Solid Creation System (SCS). Sony stopped manufacturing SL systems for D-MEC in 2007. In 1988, Asahi Denka Kogyo introduced the first epoxy resin for the CMET SL machine. The following year, Japan Synthetic Rubber (now JSR Corp.) and DSM Desotech began to offer resins for the Sony/D-MEC machines.

In 1990, Electro Optical Systems (EOS) of Germany sold its first Stereos stereolithography system. The same year, Quadrax introduced the Mark 1000 SL system, which used visible light resin. The following year, Imperial Chemical Industries introduced a visible light resin product for use with the Mark 1000. ICI stopped selling its resin about one year later when Quadrax dissolved due to a legal conflict with 3D Systems.

Introduction of non-SL systems

In 1991, three AM technologies were commercialized, including fused deposition modeling (FDM) from Stratasys, solid ground curing (SGC) from Cubital, and laminated object manufacturing (LOM) from Helisys. FDM extrudes thermoplastic materials in filament form to produce parts layer by layer. SGC used a UV-sensitive liquid polymer, solidifying full layers in one pass by flooding UV light through masks created with electrostatic toner on a glass plate. LOM bonded and cut sheet material using a digitally guided laser. Cubital and Helisys have not been in business for many years.

Selective laser sintering (SLS) from DTM (now a part of 3D Systems) and the Soliform stereolithography system from Teijin Seiki became available in 1992. Using heat from a laser, SLS fuses powder materials. The Soliform technology

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was originally developed by DuPont under the Somos name and was subsequently licensed to Teijin Seiki for exclusive distribution rights in parts of East Asia. Also in 1992, Allied Signal introduced vinylether Exactomer resin products for SL.

In 1993, Soligen commercialized direct shell production casting (DSPC). Using an inkjet mechanism, DSPC deposited liquid binder onto ceramic powder to form shells for use in the investment-casting process. Massachusetts Institute of Technology (MIT) invented and patented the process that Soligen used. The company shut down its operations in January 2006. The same year, Denken introduced an SL system that uses a solid-state laser. Denken's SL system was one of the first to fit on a bench top and was introduced at a low price, compared to other SL systems that were on the market.

Also in 1993, 3D Systems and Ciba commercialized their first epoxy resin product. At around the same time, the QuickCast build style was introduced. QuickCast is a method of producing investment-casting patterns that are mostly hollow, making it possible to burn them out without fracturing the ceramic shell. It is still used to this day.

1994 was a year of many new additive-manufacturing system introductions. ModelMaker from Solidscape (then called Sanders Prototype) became available, as did new systems from Japanese and European companies. ModelMaker deposits wax materials using an inkjet print head. One of the new Japanese systems was a small stereolithography machine from Meiko targeted mainly at the makers of jewelry. (Meiko ended its SL business in 2006.) Meanwhile, Kira Corp. commercialized Japan's first non-stereolithography system. Called Solid Center, it uses a standard laser printer engine, toner, and an *x-y* plotter and knife to produce wood-like models by paper lamination. Kira referred to Solid Center as the first plain-paper 3D printer.

Also in 1994, Fockele & Schwarze (F&S) of Germany introduced a stereolithography machine, but on a limited basis. The German company EOS commercialized a machine called EOSINT based on laser-sintering technology the same year. Japan's Ushio (now called Unirapid Inc.) sold its first stereolithography machine in 1995.

Introduction of low-cost 3D printers

In 1996, Stratasys introduced the Genisys machine, which used an extrusion process similar to FDM but based on technology developed at IBM's Watson Research Center. After eight years of selling stereolithography systems, 3D Systems sold its first 3D printer (Actua 2100) in 1996, using a technology that deposits wax material layer by layer using an inkjet printing mechanism.

The same year, Z Corp. launched its Z402 3D printer, primarily for concept modeling. Based on MIT's inkjet printing (3DP) technology, the Z402 produced models using starch- and plaster-based powder materials and a water-based liquid binder. Also in 1996, Schroff Development began to sell its semi-automated paper lamination system for under $10,000.

Personal Modeler 2100 from BPM Technology was sold commercially in 1996. The ballistic particle manufacturing (BPM) process deposited wax materials using an inkjet print head. The company ceased operations in October 1997. Also in 1996, Aaroflex commercialized DuPont's Somos stereolithography

technology in the U.S. The same year, Kinergy of Singapore began to sell its Zippy paper lamination systems, which functioned similarly to the LOM process.

AeroMet was founded in 1997 as a subsidiary of MTS Systems Corp. The company developed a process called laser additive manufacturing (LAM) that used a high-power laser and powdered titanium alloys. Until it shut down in December 2005, AeroMet manufactured parts for the aerospace industry as a service provider. Also in 1997, Ciba purchased the Exactomer resin business from Allied Signal.

In 1998, Beijing Yinhua Laser Rapid Prototypes Making & Mould Technology Co., Ltd. stepped up the promotion of its products. Since 1996, Tsinghua University in Beijing—the original developer of the systems—has offered technologies similar to FDM and other additive processes. The same year, Autostrade introduced its E-DARTS stereolithography system to companies in Japan for $25,000. Also in 1998, Optomec commercialized its laser-engineered net shaping (LENS) metal powder system based on technology developed at Sandia National Labs.

In March 1999, 3D Systems introduced a faster and less expensive version of Actua 2100 called ThermoJet. A month earlier, the company also began to sell its SLA 7000 system for $800,000. It was the most expensive plastic-based AM system on the market at the time. In April 1999, the Extrude Hone AM business (now Ex One) installed its first ProMetal RTS-300 machine for building metal parts at Motorola. The system is based on MIT's 3DP inkjet-printing technology. Fockele & Schwarze of Germany introduced its steel powder-based selective laser-melting system, developed in cooperation with the Fraunhofer Institute for Laser Technology.

Also in 1999, Röders began to sell its controlled metal buildup (CMB) machine, based largely on technology developed at the Fraunhofer Institute for Production Technology. The same year, DSM purchased the Somos business from DuPont.

In January 2000, Helisys announced that Toyoda Machine Works of Japan would manufacture and sell LOM systems in Japan. In June, Toyoda showed its own machine based on LOM technology at a large exhibition in Tokyo. The same month, Sanders Design International announced the development of a machine named Rapid ToolMaker (RTM). Also in January, Sanders announced that it had licensed the RTM technology to the German company Buss Modeling Technology (BMT), formerly Buss Müller Technology, with the intent to manufacture and sell it in Europe. At around the same time, BMT announced that it would manufacture and sell a color 3D printer based on powder and binder technology developed by Aad van der Geest of the Netherlands. The process was similar to the 3DP process from Z Corp.

New generation machines

April 2000 was a month full of new technology introductions. Objet Geometries of Israel announced Quadra, a 3D inkjet printer that deposited and hardened photopolymer using 1,536 nozzles and a UV light source. Sanders Prototype (now Solidscape) introduced PatternMaster, a machine designed to produce precision wax patterns. Precision Optical Manufacturing (POM) announced direct metal deposition (DMD), a laser-cladding process

that produces and repairs parts using metal powder. POM began system sales in early 2002 and continues to offer DMD as a service. Z Corp. introduced its Z402C machine, the world's first commercially available multi-color 3D printer.

In July 2000, Stratasys introduced Prodigy, a machine that produces parts in ABS plastic using the company's FDM technology. In October, Sanders Prototype Inc. changed its name to Solidscape Inc. to avoid market confusion with Sanders Design International. In November 2000, Helisys closed its doors after selling more than 375 systems worldwide over a period of nine years. The same month, Helisys founder and LOM inventor Michael Feygin announced the formation of Cubic Technologies. The new company absorbed most of the assets of Helisys. Also in November, Teijin Seiki announced that it would acquire the CMET SL technology from NTT Data. By March 2001, the acquisition was complete and the expanded stereolithography manufacturer changed its name to CMET Inc.

In 2001, Solidimension (now Solido) of Israel quietly introduced its desktop machine, a technology that laminates thin sheets of PVC plastic. The company was slow to ship machines to customers, even to beta test sites, and had planned to sell machines in 2002, but did not. Finally, in 2004, it sold its first machines to companies in Japan. Also in 2001, Aaroflex and Cubital quietly disappeared from the industry. Israel-based Cubital was one of the first companies to commercialize an additive-manufacturing process and sold 33 systems over a span of eight years.

In February 2001, 3D Systems acquired OptoForm, a French company that developed a stereolithography method of using non-liquid photocurable materials. The OptoForm technology is capable of using ceramics, metals, and various composite materials in the form of pastes.

In March 2001, Objet Geometries began to ship a beta version of its Quadra 3D printer. In May 2001, Solidica disclosed technical details on its ultrasonic consolidation process, and began to ship machines to beta customers in late 2001 and early 2002. The technology combines ultrasonic welding and CNC machining to produce aluminum parts. In September 2001, Stratasys began the commercial shipment of its FDM Titan, a machine capable of producing parts in polycarbonate, ABS, polyphenylsulfone, and a polycarbonate–ABS blend.

In August 2001, 3D Systems completed its acquisition of DTM. The merger sparked an intense investigation by the Antitrust Division of the U.S. Department of Justice. In September 2001, 3D Systems acquired RPC Ltd., a small stereolithography resin producer in Switzerland. This occurred on the heels of Huntsman (then Vantico and formerly Ciba) severing its long-term distribution relationship with 3D Systems.

At EuroMold 2001 in late November, Envisiontec of Germany showed its Perfactory machine. The technology uses acrylate photopolymer and digital light processing (DLP) technology from Texas Instruments to harden an entire layer at once. Also at EuroMold, Z Corp. introduced its Z810, a system that prints parts in a 500 x 600 x 400 mm (20 x 24 x 16 inch) build volume using 1,800 jets from six HP print heads.

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In 2001, Generis GmbH of Germany commercialized its large GS 1500 system. The system uses an inkjet-printing technique to fuse together sand to produce sand cores and molds for metal castings. Later in the year, ProMetal installed its first RTS-300 machine in Europe.

Also at EuroMold 2001, Objet Geometries introduced its QuadraTempo product, an improved version of its Quadra machine. EOS announced its DirectSteel 20-V1 product, a steel-based powder consisting of particles 20 microns (0.0008 inch) in size. The powder is used to produce metal parts in layers that are 20 microns (0.0008 inch) in thickness. At around the same time, the company introduced its EOSINT 380, a laser-sintering machine that offered speed improvements.

Concept Laser GmbH, a Hofmann company in Germany, introduced a new system at EuroMold 2001 that combines laser sintering, laser marking, and laser machining. The machine uses an yttrium-aluminum-garnet (YAG) laser and stainless steel powder to produce fully dense parts. Shanghai Union Technology Co., Ltd. (also known as Uniontech) of Shanghai, China, began to sell its SL machines in China in 2001.

In 2001, RSP Tooling LLC was formed. RSP stands for rapid solidification process, a steel spray technique developed at the Idaho National Engineering and Environmental Laboratory (INEEL). In January 2002, RSP Tooling announced that it had reached an agreement to obtain an exclusive license for the RSP technology. An alpha test machine was completed in February 2002. Ohio-based Belcan served as a development partner and investor.

In early 2002, Stratasys introduced its Dimension product at a price of $29,900. The Dimension machine, which deposits ABS plastic, is based on the former Prodigy product. The same year, Concept Laser GmbH began to sell its M3 Linear machine. Also in 2002, Envisiontec GmbH began to sell its Perfactory and Bioplotter machines. The Bioplotter produces scaffold structures from various biomaterials for tissue engineering.

Wuhan Binhu Mechanical & Electrical Co., Ltd. of China began to sell lamination, laser sintering, stereolithography, and plastic extrusion (similar to FDM) systems in 2002. The same year, Solidscape introduced its T66 product, a lower-priced version of its drop-on-demand inkjet-based machine. Phenix Systems of France sold its first Phenix 900 system in 2002. The machine uses solid-phase sintering to produce ceramic and metal parts.

After more than two years of offering services only, POM began to sell its direct metal deposition machine in 2002. It uses a CO_2 laser, a 3-axis, overhead gantry CNC-motion system, and metal powders to repair tooling and aid in the production of tooling components. Meanwhile, Schroff Development stopped selling its inexpensive paper lamination machines.

Menix, Co., Ltd. of Korea sold it first VLM300 variable lamination machines in 2002. This system uses a 4-axis, hot-wire cutter to slice through high-density polystyrene sheets at an angle to minimize stair stepping. The machine is currently priced at about $18,000.

In February 2003, Z Corp. introduced its ZPrinter 310 system. The product, then priced at $29,900, uses technology similar to the company's other powder-based 3D printers. It replaced the Z400 product. The same month, EOS announced that it had sold its first two EOSINT laser-sintering machines in North America.

In May 2003, Sony Precision Technology America began to market the Sony stereolithography machines in the U.S. As part a settlement between 3D Systems and the U.S. Department of Justice, Sony purchased a license from 3D Systems to sell stereolithography in North America. Active sales of the machine occurred later that year.

In mid-2003, Solidscape introduced its T612 system for making wax patterns for investment castings. The basic technology is similar to Solidscape's previous systems, although the T612 is faster and builds much bigger parts. Around the same time, Envisiontec launched the sale of its systems in the U.S.

In September 2003, it was announced that Stratasys would serve as Objet Geometries' exclusive distributor for its Eden products in North America. The distribution agreement ended in December 2006.

In late 2003, 3D Systems began to sell and ship its InVision 3D printer, a machine that jets and hardens photopolymer, similar to Objet's machines. 3D Systems priced the machine at $39,900. The company introduced the InVision HR (high resolution) version of the machine in April 2004 for $59,900. Chubunippon began to sell its low-cost Wizaray stereolithography system in 2003. The machine built acrylate parts that fit inside a 100 x 100 x 100 mm (4 x 4 x 4 inch) build volume and sold for about ¥998,000 (~$10,184).

At EuroMold 2003, EOS introduced its EOSINT M 270 direct metal laser-sintering machine. The system uses a fiber laser rather than a CO_2 laser, which is used in the EOSINT M 250 Xtended machine. Another German company, Trumpf, introduced its TrumaForm LF and TrumaForm DMD 505 machines at EuroMold. The LF machine uses a 250-watt laser and fiber optic cable to direct light onto a bed of pure powder metal. Trumpf partnered with POM to produce the DMD 505 machine. The 505 includes a 5-axis motion system.

In March 2004, Stratasys introduced the "Triplets," which consisted of three variations of the FDM Vantage machine. Prices ranged from $99,000 to $195,000. The machines are capable of processing both ABS and polycarbonate materials.

In Q2 2004, Envisiontec introduced the Vanquish photopolymer-based system. The Vanquish machine uses digital light processing technology to solidify an entire layer at once. Unlike the company's Perfactory system, Vanquish works in a similar way to traditional stereolithography systems, with the build platform moving downward with each layer.

DSM Somos introduced several new resins at the April 2005 SLA/SLS user conference, including a nanocomposite material, a high-elongation material, a low-durometer material, a UL94 V0 flame-retardant material, and a material that can withstand relatively high temperatures.

In July 2004, the ProMetal division of Ex One (then Extrude Hone) introduced the small RX-1 metal-based machine. Maximum part size is 40 x 60 x 25 mm (1.6 x 2.4 x 1 inch). The RX-1 is targeted at educational and research customers.

Also in July, 3D Systems announced the Bluestone nanocomposite SL resin. The same month, 3D Systems began to ship the InVision HR, a high-resolution 3D printer targeted at the jewelry market. The Sinterstation HiQ, also released in July, added new closed-loop thermal controls and scanning options aimed directly at process improvement for part production applications. This technology was also offered as an upgrade to the Sinterstation 2500plus and Vanguard systems.

Solidica sold and installed a new version of its ultrasonic consolidation system, called Formation, in September 2004. The system was priced at about $400,000. The following month, 3D Systems introduced its dual-vat Viper HA stereolithography system for the hearing aid industry. In November, Objet introduced its Vero FullCure 800 series opaque-colored materials. They offer improved mechanical properties and better detail visualization.

At EuroMold 2004, EOS introduced the EOSINT P 385, a plastic material system capable of thinner layers than were possible with its predecessor, the EOSINT P 380. Also at EuroMold, Concept Laser of Germany introduced the M1 cusing laser-melting machine. The machine can process all of the metals of the M3 Linear but it does not support laser erosion or laser marking. Next Factory (now DWS) introduced the DigitalWax 010 and DigitalWax 020 systems. Both use a solid-state laser to harden photopolymer, and were priced at €25,000 and €35,000, respectively.

Also in December 2004, Solidscape introduced the T66 Benchtop and T612 Benchtop systems for $40,000 and $50,000, respectively. The systems do not require air-conditioning units, so they are smaller and lighter than the previous machines.

In March 2005, Z Corp. released its latest color 3D-printing system, the Spectrum Z510. It offers a larger build volume, produces better quality parts than the Z406, and is less expensive at $49,900. The same month, Stratasys dropped the price of the Dimension SST from $34,900 to $29,900. The machine offers a soluble support removal system that automates the process.

In April 2005, 3D Systems unveiled the Sinterstation Pro, a large-frame laser-sintering machine with part breakout, powder handling, and recycling. It is built on the HiQ technology and includes removable build modules and digital scanning. The InVision LD, manufactured by the Israeli company Solido and rebranded by 3D Systems, was introduced at a price of $22,900. This system builds parts by selectively laminating PVC sheet material.

In June 2005, Aspect Inc. of Japan showed its SEMplice laser-sintering machine at a large exhibition in Tokyo. The same month, DSM Somos sold its laser-sintering technology and patent portfolio to Valspar Corp., a large manufacturer of coatings and laser-sintering powders in Switzerland. A month later, Contex Scanning Technologies, a Danish manufacturer of wide-format document scanners, acquired Z Corp. In August 2005, Objet Geometries introduced the FullCure Tango line of flexible materials for its PolyJet systems.

October 2005 was an active month. Stratasys launched its RedEye RPM paid parts service business with online quoting and 60 FDM and PolyJet machines. Objet Geometries introduced the Eden500V, a large-format PolyJet 3D printer for $170,000. Z Corp. introduced the $25,900 ZPrinter 310 Plus, which replaced the ZPrinter 310. 3D Systems announced the large Viper Pro SLA, a modular system capable of running single or dual vats of resin.

In November 2005, 3D Systems announced that it would relocate its headquarters to Rock Hill, South Carolina. The company also announced its new DuraForm EX polyamide material for its Sinterstation Pro systems. The same month, Ex One's ProMetal division introduced the sand-based S-Print machine at a base price of $500,000. Envisiontec launched a new version of its Perfactory machine. Meanwhile, MCP Tooling Technologies (now MTT Technologies Group) introduced the SLM ReaLizer 100 selective laser-melting machine.

Voxeljet Technology GmbH of Germany introduced its VX800 machine and showed parts from it at EuroMold 2005. The large powder-based system uses 3DP technology originally developed at MIT and commercialized by Z Corp. The company sold its first machine in 2005.

In December 2005, AeroMet, a division of MTS Systems Corp., ceased operations. MTS said in an announcement that making titanium parts for the aerospace industry was not a profitable business model.

The Swedish company Speed Part (now Sintermask GmbH of Germany) began to ship its system in early 2006. The machine uses infrared lamps to project light through a mask to sinter an entire layer of powder. The cycle time for each layer is reportedly less than 10 seconds, regardless of the area sintered.

In January 2006, Stratasys signed an agreement with Arcam to be the exclusive distributor in North America for electron beam melting (EBM) systems. Meanwhile, Stratasys lowered the price of its Dimension BST and SST machines from $24,900 and $29,900 to $18,900 and $24,900, respectively. In response to these lower prices, Z Corp. lowered the price of its ZPrinter 310 Plus from $25,900 to $19,900.

Also in January, Objet Geometries introduced its Eden350/350V platform, which replaced its popular Eden330/333 system. At the same time, the company introduced its Eden250 3D printer for $60,000. Soligen shut down its operation the same month after more than 12 years in business.

In February 2006, 3D Systems announced its InVision DP (dental professional) system that includes an InVision 3D printer and 3D scanner for the dental market. Stratasys added the Vantage X systems starting at $99,000 and reduced the price of its Vantage i machine to $85,000.

3D Systems reduced the price of its InVision LD (plastic lamination) product from $22,900 to $14,900 in March 2006. Also in March, the company filed a patent infringement lawsuit against Envisiontec and Sibco. In Q2 2006, EOS introduced stainless steel and cobalt–chrome materials.

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In April 2006, Stratasys introduced the Dimension 1200 BST and SST systems priced at $21,900 and $29,900, respectively. The following month, Desktop Factory (Pasadena, California) announced that it was developing a 3D printer priced in the $5,000 to $7,000 range. The device uses an inexpensive halogen light source and drum-printing technology to build parts additively from plastic powder.

In May 2006, DSM Somos showed its NanoTool, a nanoparticle-filled photopolymer for SL with high-heat-resistant capabilities. DSM also introduced ProtoCast AF 19120, a completely antimony-free, low-ash-content SL resin targeted at investment casting. DSM Somos also unveiled its new high-accuracy, ABS-like SL materials, ProtoGen O-XT 18120 and O-XT 18420.

Also in May 2006, Sony Manufacturing Systems ended its stereolithography sales in North America. Under a licensing agreement with 3D Systems, Sony began to establish an SL sales organization in California in Q3 2002. In a span of more than three years, the company sold four systems.

The same month, 3D Systems released its Accura 60 photopolymer, which is said to mimic polycarbonate. The following month, the company announced two authorized service providers: Integra Services for its laser-sintering equipment and Total C S Team for SL equipment.

The German company Trumpf discontinued its TrumaForm LF machine in Q2 2006. The machine constructs parts in a powder bed by selectively melting powder with a Trumpf disk laser.

In August 2006, EOS launched its cobalt–chrome powder material for the EOSINT M 270 systems. The same month, Z Corp. introduced its ZScanner 700 handheld 3D scanner for $39,900. In October 2006, EOS announced the commercial availability of 17-4 stainless steel for use with its EOSINT M 270 equipment.

In November 2006, 3D Systems opened its new headquarters in Rock Hill, South Carolina, and Stratasys opened a new office in Shanghai, China.

At EuroMold 2006, several new products were introduced. EOS unveiled the Formiga P 100 laser-sintering system, a new machine that was designed from the ground up. It currently sells for €150,000 to €170,000. EOS also introduced two new higher-throughput machines, the EOSINT P 390 and EOSINT P 730. Voxeljet Technology showed its VX800 machine, which uses PMMA thermoplastic powder. Envisiontec introduced its small Perfactory Desktop System. MTT (then MCP Tooling Technologies) introduced its new SLM ReaLizer 100 selective laser-melting machine. Next Factory (now DWS) introduced a faster stereolithography machine, as well as a much larger system.

Aspect Inc. of Japan shipped its first SEMplice laser-sintering machines to customers in Q4 2006, a product it introduced more than a year earlier. Speed Part of Sweden (now Sintermask of Germany) sold its first systems in 2006. In Q4 2006, Meiko of Japan stopped manufacturing and selling SL systems. Near the end of 2006, Trumpf ended its agreement with POM to sell the large DMD 505 machine in Europe. At the end of the year, Stratasys stopped the distribution of the Eden PolyJet products for Objet Geometries. Meanwhile,

Objet opened a sales and support office in Billerica (near Boston), Massachusetts. In December 2006, Stratasys installed the first Arcam EBM machine in the U.S.

In January 2007, 3D Systems announced the V-Flash 3D printer. It uses film transfer and flash-imaging technology. The machine was expected to sell and ship around mid-2007 at a price of $9,900. The same month, Stratasys launched the new Dimension Elite 3D printer for $32,900.

Solidscape released two market-specific models of its T66 machine, the D66 for dental applications in February and the R66 for the jewelry applications in March. Both are currently about $36,000. Around the same time, Desktop Factory received “pre-sales” for most of the 200 units that it had planned to deliver in 2007. The 125ci 3D printer was expected to be in full production in July or August 2007.

In March 2007, Z Corp. introduced the ZPrinter 450, the first color 3D printer to break the $40,000 price point. The most interesting feature of the system is its automated removal and recycling of loose powder. The ZPrinter 450 is the first product from Z Corp. to be truly office friendly. Also in March, Sony Manufacturing Systems stopped manufacturing the Solid Creation System for D-MEC of Japan. This came after 18 years of manufacturing the family of stereolithography systems.

At the 2007 3DSUG Users Conference, DSM Somos introduced the DMX-SL 100 high-impact-resistance material for rigorous prototyping and manufacturing applications. It also introduced WaterClear Ultra with ABS-like properties, resistance to water, and improved clarity. Huntsman released a resin, initially named 71640, for HeCd-based SL systems that offered low viscosity and good impact resistance. 3D Systems announced the Accura 55 resin that mimics ABS.

Also at the 3DSUG event, Advanced Laser Materials released a new fire-retardant polyamide for laser-sintering systems. It passed the 60-second vertical burn test and offers Nylon 11-like properties. The company also showed a highly recyclable polyamide composite material for LS. SLAMaterials introduced three SL resins: a clear material called Hi-Rezz ICE, Hi-Rezz MED for medical applications, and Hi-Rezz X-factor that offers high strength and high-temperature capabilities.

In April 2007, Arcam introduced its larger build volume A2 electron beam melting (EBM) machine. EOS introduced its Formiga P 100 laser-sintering system to the American market the following month. Stratasys announced its FDM 200mc machine and the ABSplus material. Z Corp. announced the zp140 composite water-curing material that requires no secondary infiltration or coating and the zp131, a whiter material for finer features. Concept Laser introduced the M2 cusing system for processing reactive materials (i.e., aluminum and titanium alloys).

In July 2007, 3D Systems introduced the Accura Extreme SL resin with improved durability and elongation. CRP Technology released its more flexible, impact-resistant Windform FX material for laser sintering. The same

month, Stratasys introduced the FDM 400mc and M30 ABS material. The following month, Stratasys opened a new global headquarters facility in Eden Prairie, Minnesota.

In September 2007, Desktop Factory accepted advance reservations for its $5,000 3D printer. The system was originally expected to become available in 2007, but shipment was delayed. Also in September, 3D Systems introduced the DuraForm HST fiber-filled polyamide for laser sintering, as well as the Accura 48HTR high-temperature SL material. Meanwhile, Objet Geometries introduced a rubber-like material called TangoPlus.

In October 2007, Voxeljet introduced its VX500 system, a smaller version of the VX800, for €270,000. DSM Somos introduced its WaterClear Ultra material in November 2007. The same month, Envisiontec issued a press announcement stating that the 3D Systems V-Flash infringes on its German patents. Accufusion delivered its first commercial system in November to Exeter Advanced Technologies (UK), an organization that is a part of a consortium led by Airbus.

December 2007 was a month full of introductions. Stratasys announced the availability of its large-frame FDM 900mc, which includes 32 parts that were manufactured with FDM technology. 3D Systems announced a new nanocomposite SL resin called Accura Greystone. EOS introduced an impact-resistant LS material called PrimePart DC and a high-elongation, flexible material called PrimePart ST.

At EuroMold 2007 in December, Envisiontec introduced the PerfactoryXede, a machine that is dramatically larger than its previous Perfactory systems. The company's Vanquish system became the PerfactoryXtreme with a new "skin." The company also introduced SI500, a material that is said to have ABS-like properties. The same month, Advanced Laser Materials announced the commercial availability of its flame-retardant FR-106 laser-sintering material.

Also at EuroMold 2007, Objet Geometries debuted its multi-material Connex500 3D-printing system. The machine is capable of printing two build materials simultaneously. It is based on Objet's PolyJet Matrix technology. The company coined the term "digital material" to describe the result of producing a composite substance using PolyJet Matrix technology. At EuroMold, Sintermask showed its Pollux 32 selective mask-sintering system, which sinters entire layers at once.

In December 2007, Mcor Technologies of Ireland informally introduced its new Matrix system that uses a blade and adhesive to laminate A4 sheets of paper. The system was expected to sell for €18,900. Also in December, former Microsoft vice president Ed Fries announced FigurePrints (Redmond, Washington). The company produces characters from the wildly successful World of Warcraft video game using color AM from Z Corp.

In January 2008, Tangible Express filed a lawsuit against 3D Systems and shut down its operations in Springville, Utah. The following month, 3D Systems settled the suit by purchasing all of the equipment from Tangible for $5.3 million. Stratasys and Arcam terminated the distribution agreement that allowed Stratasys to distribute the EBM products in North America. Subsequently, Arcam set up its own direct sales channel in the U.S.

The same month, Stratasys introduced the FDM 360mc to replace the Vantage machines. 3D Systems released the next version of its Multi-Jet Modeling machine, the ProJet HD3000.

In February, 3D Systems and MTT (then MCP Tooling Technologies) announced a private label agreement in which 3D Systems would distribute the selective laser-melting systems in the U.S. Stratasys announced its Dimension 1200es 3D printer with ABSplus material. Also, the company announced its RedEye architectural modeling division—RedEye ARC.

Stratasys unveiled a biocompatible FDM material, ABS-M30i, in March 2008. The same month, 3D Systems announced a collaborative materials agreement with Trial Corp. of Japan to develop new LS materials. DSM Desotech (a.k.a. DSM Somos) filed a lawsuit against 3D Systems alleging anticompetitive conduct and patent infringement. John Kawola, a longtime Z Corp. employee, replaced Tom Clay as CEO of Z Corp. MCP Tooling Technologies changed its name to MTT.

In April 2008, 3D Systems began to ship its V-Flash desktop modeler, but then soon stopped shipment. Sales and shipments were still on hold as of April 2009. The same month, Solidscape introduced its T76 precision wax-printing system.

In Q2 2008, Netherlands-based Shapeways, a company that is a part of the Philips Electronics' incubator program, rolled out its service to the world. The company gives consumers a relatively easy way to convert 3D designs into parts or products. Shapeways offers a range of "creator" tools that simplifies the process of designing custom products for consumers.

In May 2008, EOS of Germany introduced its high-elongation polyamide PrimePart DC for plastic laser sintering and Stainless PH1 for its direct metal laser-sintering platforms. Optomec (Albuquerque, New Mexico) released its new LENS MR-7 machine with a fiber laser, dual-powder feeder, and integrated thermal imager for process monitoring. Optomec also entered into an agreement with Manz Manufacturing of Germany for using the M3D Aerosel Jet deposition system for printing photovoltaic cells.

Arcam of Sweden released the Titanium Grade 2 material for its electron beam melting systems the same month. 3D Systems announced an agreement with 3M to combine its dental-scanning systems as options with 3D Systems' 3D-printing systems. In July 2008, 3D Systems, Boeing (USA), EOS, Evonik of Germany, and MTT created a Direct Manufacturing Research Center with the University of Paderborn (Germany). Objet Geometries announced the DurusWhite FullCure 430 polypropylene-like material. 3D Systems introduced the iPro 9000 SLA Center stereolithography system as a replacement to its Viper Pro in August 2008. The company also introduced its ProJet SD 3000 3D printer.

In September 2008, Nuvotronics (Blacksburg, Virginia) announced the commercial availability of its PolyStrata microfabrication technology for very small electronic and sensing devices. Milwaukee School of Engineering licensed its TetraLattice Technology, developed in conjunction with Materialise of Belgium, to DSM Somos.

At 3D Systems' World Conference in October 2008, the company showed the large-frame iPro 9000 XL SLA Center and the iPro 8000 MP SLA Center, which has a 50 mm (2 inch) build height and targets the hearing aid, dental, and medical industries. A new ultra-clear SL material, Accura ClearVue, was also shown. The ProJet CP 300 RealWax 3D printer and a large-format ProJet 5000 were released. The sPro 140 and 230 SLS Centers were shown and have replaced the Sinterstation Pro series. The company also announced the availability of its polypropylene laser-sintering material, DuraForm PP 100, developed jointly with TRIAL Corporation of Japan.

At the October TCT 2008 event in Coventry, England, MTT released a larger selective laser-melting machine, the SLM 250-300. The machine offers a 250 x 250 x 300 mm (9.8 x 9.8 x 11.8 inch) build volume with automated powder handling and recycling. Also at the event, Mcor Technologies of Ireland officially launched its Matrix 3D printer. It uses standard A4 sheets of paper, a water-based adhesive for bonding the sheets, and a mechanical blade for cutting the cross sections. It is priced at about €25,000.

Also at TCT 2008, Huntsman Advanced Materials of Switzerland announced the development of an entirely new additive-manufacturing process based on MLS MicroLightSwitch technology. It uses 40,000 microshutters and a raster approach to direct UV light onto the surface of photopolymer. October was the month that Z Corp. chose to release the high-resolution, 24-bit color ZPrinter 650 for $60,000. Objet introduced the $40,000 Alaris30 PolyJet machine that produces 28-micron (0.0011-inch) layers using the VeroWhite FullCure 830 material.

FigurePrints produced 1,700 custom products using AM for players of World of Warcraft in October 2008. This came only 10 months after the company launched the manufacturing service. In November, another consumer-oriented service, JuJups.com by Genometri of Singapore, began making custom Christmas ornaments. The customer submits a JPG image of a face, which is then used to produce an angel in color using a 3D printer from Z. Corp. The same month, Objet released its Eden260V machine capable of running a range of materials, including the Vero, Tango, and DurusWhite.

At EuroMold 2008 in December, Huntsman Advanced Materials introduced the Araldite Digitalis, a machine based on MLS MicroLightSwitch technology. The chemistry giant believes that it is faster and more accurate than stereolithography. Huntsman also announced a new material, SL 7820. It is white in its uncured form, but turns black upon exposure to UV, resulting in black SL parts without secondary painting.

Also at EuroMold, EOS unveiled a new large-frame, high-temperature, laser-sintering platform, the EOSINT P 800. It is capable of processing polymers up to a temperature of about 385°C (725°F). This expands AM to a new range of thermoplastics, such as PEEK, which EOS also introduced at EuroMold. Stratasys announced that it would offer ULTEM 9085 for its FDM 900mc and 400mc machines. The material is widely used in aircraft interiors for its flame redundancy and low smoke emissions. Concept Laser of Germany released an updated M1 cusing system. The new machine has a more powerful laser and a 250 x 250 x 250 mm (9.8 x 9.8 x 9.8 inch) build volume.

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Also in December 2008, Stratasys introduced a vapor-honing product called Fortus Finishing Stations for finishing FDM parts made in ABS. Electronic Arts of Redwood City, California and Z Corp. announced the availability of Spore Sculptor, a service for printing models of Spore creatures. Near the end of 2008, 3D Systems sold its Grand Junction, Colorado facility.

In January 2009, 70 individuals from around the world met at the ASTM International headquarters near Philadelphia, Pennsylvania to establish ASTM Committee F42 on Additive Manufacturing Technologies. The committee was created to produce standards on testing, processes, materials, design (including file formats), and terminology. The same month, the Dimension 3D Printing Group of Stratasys introduced the uPrint Personal Printer for $14,900. The machine uses the ABSplus material and soluble supports.

Also in January, Shapeways (Eindhoven, Netherlands) introduced Shapeways Shops. It allows artists, designers, or anyone to set up “storefronts” and upload 3D models to sell to the public. The products are manufactured on an AM system and shipped directly to the consumer by Shapeways. Products include sculptures, jewelry, figurines, and a wide range of other consumer-oriented products. Prices start at a few dollars.

In February 2009, Jérémie Pierre Gay founded Create It Real (Aalborg, Denmark). He was planning to offer a 3D printer called the Platon in 2010. Also in February, EOS and Victrex of the UK announced a new PEEK material, PEEK HP3, for use in the high-temperature EOSINT P 800 machine. Stratasys announced a price reduction on its Elite and BST 1200es Dimension machines in March 2009. 3D Systems formed an alliance with Dreve GmbH of Germany to develop and market dental application solutions.

FigurePrints announced the availability of its custom additive-manufacturing service in Europe in March 2009. The same month, ReaLizer GmbH of Germany introduced the SLM 50, the first selective laser-melting machine that fits on a bench top. The system measures 800 x 700 x 500 mm (31.5 x 27.6 x 19.7 inches) and processes stainless steel, tool steel, cobalt–chrome, and gold.

In April 2009, EOS bought a controlling interest in Advanced Laser Materials, a developer and manufacturer of laser-sintering materials. EOS and Trumpf of Germany withdrew their U.S. lawsuit against MTT Technologies after MTT agreed to license certain laser-sintering patents owned by EOS and Trumpf.

Also in April, Bits from Bytes of England released the RapMan 3D printer kit (£750) based on the RepRap open-source system launched at Bath University of England. It uses an extrusion head similar to FDM, includes software for slicing STL files, and sends the data to the machine in G-code format. The same month, Stratasys released its new SR-30 support material for its ABS M-30 material. The material dissolves about 50% faster than its predecessor.

In April 2009, MakerBot Industries introduced its Cupcake CNC product based on the RepRap open-source system in April 2009. Kits are available for $750. ProMetal RCT, a division of Ex One, was named the North American distributor for the Voxeljet 3D-printing process.

In May 2009, EOS sold its first EOSINT P 800 laser-sintering machine for processing PEEK and other high-temperature materials. Envisiontec introduced

its ULTRA bench-top DLP-based system for $35,000. Solidscape unveiled its PreXacto line of 3D dental printers and its new DentaCast material. 3D Systems commenced shipment of its $9,900 V-Flash 3D printer that was announced in January 2007.

In June 2009, Z Corp. released its new water-curable zp150 composite build material. 3D Systems released DuraForm FR 100, a halogen-free, flame-retardant material for laser sintering that meets aerospace smoke and toxicity requirements. Also in June, Objet Geometries announced its Connex350 system for about $200,000. Like the Connex500, it uses the PolyJet Matrix technology to print multiple digital materials with different properties.

Also in June, Fujifilm Dimatix unveiled its new Dimatix Materials Printer DMP-3000, which offers a print area of 300 x 300 mm (11.8 x 11.8 inches). It uses high-definition print heads that users can fill with their own fluids. The printer is similar to Optomec's Aerosol Jet non-contact, maskless system for direct-write electronics. The Dimatix system is targeted at the printed electronics market for research and development.

In August 2009, 3D Systems acquired the assets of Desktop Factory from Idealab (Pasadena, California). Desktop Factory created an industry buzz when it announced a $5,000 machine in May 2006. The system uses an inexpensive halogen light and drum-printing technology to build parts in plastic powder, but the company was unable to commercialize it. Stratasys announced the compatibility of its large-frame Fortus 900mc machine with ULTEM 9085, PC-ABS, PC-ISO, and ABS-M30i in August.

Objet announced a new material pack in October 2009 for its Connex line of PolyJet Matrix printers that gave users 18 additional materials with Shore A hardness from 27 to 95. TangoBlackPlus FullCure, a material with rubber-like properties, was also released. The same month, Materialise and other volunteer companies turned over the RP4Baghdad humanitarian project to Doctors Without Borders. The effort provided medical assistance to civilians in Iraq.

The same month, ASTM International Committee F42 on Additive Manufacturing Technologies published standard terminology for the industry—the first standard produced by the group. 3D Systems purchased Acu-Cast Technologies (Lawrenceburg, Tennessee) and launched it 3Dproparts service bureau in October 2009. As the first of several service provider acquisitions, 3D Systems marked the entrance into the paid parts business, effectively competing against its own customers.

Z Corp. announced its automated monochrome ZPrinter 350 machine with automated material loading and integrated material recycling in October 2009. DSM Somos announced that its WaterShed XC 11122 and ProtoGen 18420 materials have been ISO 10993 certified for in vitro cytotoxicity and sensitivity. In November 2009, 3D Systems acquired AdvaTech Manufacturing (Goodland, Indiana).

At EuroMold 2009 in December, EOS announced two new plastic laser-sintering machines: the EOSINT P 395 and EOSINT P 760. The large-frame P 760 machine can monitor laser power during the build. EOS released NickelAlloy IN718 (an Inconel alloy) and Al-Si10-Mg (an aluminum alloy) for its M series metals-based machines. 3D Systems announced the ProJet 5000,

with a build volume of 550 x 393 x 300 mm (21.7 x 15.5 x 11.8 inches). It uses the VisiJet MX photopolymer material with a wax support material.

Also at EuroMold, Solido relaunched its plastic lamination system and created a lot of attention in the process. The SD300 Pro system is priced from $2,950 to $9,950 in the U.S., along with the $2,950 purchase price for required supplies, bringing the total to $14,950. Carima of South Korea introduced a family of three DLP-based visible light photopolymer 3D printers. They are priced from $57,000 to $59,000 and build parts upside down, similar to the Perfactory system from Envisiontec. Voxeljet released its new large-frame machine, the VX800HP, with increased throughput and higher resolution. 3D Systems expanded its 3dproparts service to Europe.

Near the end of 2009, Steven Adler of A3DM formed an independent Solidscape users group for jewelry designers and manufacturers who use the Solidscape equipment. An online forum was established at solidscapeusergroup.com. Meanwhile, a design-your-own toy website, MAQET (maqet.com), was launched by artist Keith Cottingham.

In January 2010, Stratasys and HP signed an agreement for Stratasys to manufacture an exclusive line of HP-branded 3D printers. Also in January, Stratasys announced the new uPrint Plus, which offers a slightly larger build volume compared to uPrint. Also included are SMART Supports, which reduce the use of support material by up to 40%. The same month, Optomec released its Aerosol Jet Display Lab System for touch screens and display applications using direct-write technology.

In February 2010, 3D Systems acquired Moeller Design (Seattle, Washington) to expand 3Dproparts. Optomec was awarded a Navy contract to continue developing the LENS process for aircraft engine repair. Materialise released its Magics Metal SG support generation software for metal additive manufacturing. CRP Technology (Italy) introduced a new laser-sintering material, WindForm LX 2.0. EWI hosted the startup meeting for a new Additive Manufacturing Consortium.

In March 2010, Stratasys extended its SMART supports capability to its entire line of Dimension and Fortus machines, allowing for build time reductions of up to 14% and reduction in support material by 40%. Netfabb released netfabb Engine for RapMan Basic. RapMan is a 3D printer from Bits from Bytes, based on the RepRap open-source development. In April 2010, 3D Systems acquired Design Prototyping Technologies (East Syracuse, New York). The same month, Materialise celebrated its 20th anniversary with its World Conference 2010 in Leuven, Belgium.

Additional developments in 2010 included the introduction of cometruejet from Microjet Technology of Taiwan. The company offers two color inkjet 3D printers using technology that is very similar to that from Z Corp. Irepa Laser formed EasyCLAD Systems to market its laser metal deposition equipment using a powder fed through a nozzle similar to LENS. The equipment can be used for laser cladding or part construction and has the capability of multi-axis and multi-material deposition.

By 2011, several industries were adopting AM as their main method of manufacture. Manufacturers of in-the-ear hearing aids were first to adopt AM

technology industry wide for the production of custom-fit shells. The dental industry began experiencing the same pervasive growth in the use of AM systems. The dental market, however, is many times larger than that of hearing aids.

The direct metals processing technologies garnered significant interest and growth. It is believed that the possibility of novel designs, combined with mechanical properties equivalent to wrought alloys with which designers are familiar, may speed the adoption of metal-based AM at a much faster rate than polymer-based AM. Biomedical and aerospace applications have led the way in this area.

When a key FDM patent expired, inexpensive equipment in the form of kits and fully assembled machines based on the RepRap open-source project became available. Since their introduction, these low-cost "personal" systems have experienced very strong growth. When critical stereolithography and laser sintering technology patents expire, expect individuals and organizations to take advantage of similar opportunities with these processes.

The ASTM International Committee F42 on Additive Manufacturing Technologies progressed impressively. The terminology standard was the first to be completed, in 2009. The F42 main ballot titled Specification for Data Exchange Format for Additive Manufacturing standard was balloted and approved in May 2011 as the first non-terminology standard. In July 2010, the ASTM F42 design subcommittee released its survey on AM design rules. This work is seen as critical to continued adoption of AM for end-use production parts.

In April 2010, Renishaw plc (UK) opened a dental manufacturing facility based on cobalt–chromium DMLS for copings and frameworks. Shapeways (The Netherlands), an online provider of consumer-oriented products, began to offer AM parts made from glass. Also in April, Stratasys began to deliver shipments of the HP-branded FDM machines.

In May 2010, Z Corp. (Burlington, Massachusetts) announced a distribution agreement with Envisiontec for its Ultra DLP-based machine. It was marketed as the ZBuilder Ultra. 3D Systems announced two new SL resins for its laser-based systems: Accura PEAK, a polycarbonate-like material, and Accura CeraMAX, a stiff, ceramic-filled material. Also in May, DSM Somos released NeXt, an ABS-like photopolymer that is durable and water resistant.

In July 2010, Delta Micro Factory Corp. (Beijing, China) introduced its extrusion-based portable personal UP! 3D printer. The machine was offered for less than $3,000. It is a single spool system with a Windows-based interface and automatic support generation. The part quality is among the best of the systems in this class.

3D Systems acquired two French service providers, CEP and Protometal, in July 2010. These purchases continued the buying spree of 3D Systems and the expansion of 3Dproparts in Europe. 3Shape (Denmark), a developer of automated software tools for orthodontics and hearing instruments, and Objet teamed to offer a dental solution for users of Objet's PolyJet technology. Z Corp. released two low-cost printers, the monochrome ZPrinter 150 at just

under $15,000, and the color ZPrinter 250 at just under $25,000. This continued the industry trend toward lower cost 3D printers.

Solidscape (Merrimack, New Hampshire) signed a distribution agreement with Hainan Giking Technology Company in China for its wax drop-on-demand printers for dental applications in August 2010. That same month, Harvest Technologies (Belton, Texas) opened a larger facility, an indication of the strength of using AM for part production—a niche that Harvest has developed. Bits from Bytes (UK) announced new software, called Axon, to drive its kit-based RapMan and BFB-3000 machine. EOS and GF AgieCharmilles partnered to create a complete tool-making process based on direct metal laser sintering for creating tools with conformal cooling and wire/ram EDM for final finishing of the tool. Also in August 2010, Quickparts announced the availability of a new online quoting system, QuickCutCNC, for traditionally machined parts.

In September 2010, Objet (Rehovot, Isreal) reduced the price of its Alaris30 printer to $24,900. Also in September, INUS (South Korea) started a service named InvisHands to create true CAD data from 3D scan point clouds. A locally installed application uploads the scan data to INUS where company staff creates the CAD model. The finished CAD model can be viewed using the local application, and if the user is satisfied, the model can be purchased and downloaded. 3D Systems acquired service provider Express Pattern (Vernon Hills, Illinois). Express Pattern is well known for creating investment-casting patterns with SL. Shapeways received $5 million in venture capital funding.

3D Systems bought Bits from Bytes (UK) in October 2010. Bits from Bytes offers low-cost, extrusion-based systems in kit and assembled forms. This gave 3D Systems a foothold in the hobbyist and educational markets. 3D Systems acquired the service provider Provel of Italy the same month. Rhodia (France) announced two new LS materials, PA 11 and PA 6.

In November 2010, Spanish research center IQS announced two new Hydroxyapatite (HA) formulations for use in 3D printers. HA is a calcifiable material often used in biomedical and dental applications. 3D printing is used for the creation of the shape, while secondary sintering is required to form the final part.

EuroMold in December 2010 brought many new product announcements. EOS introduced the EOSINT M 280 system. The machine's dual-mode system can run in nitrogen or argon environments, enabling customers to use materials such as stainless steel and cobalt–chrome, as well as titanium alloys. NickelAlloy IN625 was announced for use with the new EOS equipment. Two new polymer materials were also released: the flame retardant PrimePart FR and the flexible Primepart ST.

Also at EuroMold, Objet released its Objet24 3D printer at a list price of $19,900. 3D Systems announced the HD 3000plus and the CPX 3000plus systems, which offer an increased build size in the *x* direction, as well as thinner layers. A new ProJet offering called the ProJet 6000, which looks like a repackaged Viper stereolithography system with various build depths, was also announced Also in December, Shapeways moved its headquarters to New York, New York.

Meetings were held in May 2010 and at EuroMold 2010 that involved the CEOs of companies in the AM industry. In January 2011, the CEOs decided to fund an initiative that would attempt to brand additive manufacturing to a broader audience. The same month, it was announced that Solido had laid off its workforce of 30 employees and entered receivership. This came after Fortissimo Capital said it would provide Solido with $8.5 million in financing. Solido sold a low-cost machine that produced parts in PVC by sheet lamination. The assets and activities of Solido were absorbed by a new company named Solid Model Ltd.

Also in January 2011, MTT Technologies split into two companies: MTT Technologies Ltd. (UK) and SLM Solutions GmbH (Lübeck, Germany). Both companies are providing selective laser melting equipment. 3D Systems purchased National RP Support (Pella, Iowa), a provider of SL equipment maintenance and hardware upgrades. Meanwhile, BotMill (Boca Raton, Florida) released the Axis 2.1 kit for $1,065 and a preassembled, extrusion-based machine Glider 3.0 for $1,395. Both are single extruder head machines based on the RepRap open-source work.

In February 2011, CRP Technology (Italy) introduced its next generation of carbon-fiber-filled material, Windform XT 2.0, with increased strength and greater elongation. Materialise announced a new material with high stiffness and good impact strength, Tusk SolidGrey 3000. The material was developed by DSM Somos for Materialise's large Mammoth SL machines. Also in February, 3D Systems acquired Quickparts (Atlanta, Georgia), an e-commerce service provider that had revenues of $25 million in 2010.

In March 2011, 3D Systems acquired the service provider Accelerated Technologies (Austin, Texas) and announced a new VisiJet e-stone material for dental-specific applications. A judgment in favor of 3D Systems against Envisiontec for patent infringement was entered in March, as well.

In April 2011, the 3DSUG, a users group previously only available to owners of 3D Systems equipment, opened its annual conference to Objet and EOS users. The 3DSUG membership voted to rename the group Additive Manufacturing Users Group (AMUG) and allow owners and users of other technologies to also become part of the group. Advanced Laser Materials (ALM), a strategic partner of EOS, took a 51% stake in Integra Services. Integra provides hardware maintenance, upgrades, and development of polymer LS systems. Objet announced new Digital Materials in April, including VeroClear, a clear, ABS-like material, and VeroWhitePlus, a multipurpose material.

Also in April 2011, Renishaw plc, known primarily for its measurement equipment, acquired MTT Technologies Ltd. Materialise purchased Marcam Engineering (Germany), a software developer for AM that is specific to metals. 3D Systems announced a two-for-one stock split the same month. 3D Systems acquired Sycode Software Solutions (India), a small company that develops plug-ins for CAD systems, and Print3D (India), which has an AM quoting plug-in for CAD software.

In May, Stratasys acquired Solidscape, a company that offers high-resolution 3D printers for creating wax patterns for investment casting, particularly for the jewelry and dental markets.

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Also in May, 3D Systems acquired The3dStudo.com, a provider of 3D models, textures, plug-ins, gallery art, and stock photos and images. The same month, 3D Systems acquired Freedom of Creation (FOC), an Amsterdam-based company that provides printable collections and 3D content. FOC's projects have received a great deal of attention over the company's 10+ years in operation. In May, 3D Systems entered into a distribution agreement with Voxeljet Technology GmbH for North America.

Other developments

Several technologies and companies have emerged and vanished over the years, including Light Sculpting (U.S.), Sparx AB (Sweden), Laser 3D (France), BMT (Germany), Röders (Germany), Schroff Development (U.S.), Desktop Factory (U.S.), and Chubunippon (Japan). All of them have developed AM systems, but they have had little or no commercial impact.

Few machines from Asia are available for sale in the U.S. at the present time. The only exception is the low-cost UP! product from Delta Micro Factory Corp. of Beijing, China. The stereolithography machines from Sony sold in the U.S. from Q4 2002 to Q2 2006. Kira Corporation sold its paper lamination machines in the U.S. for a short period beginning in January 2001.

Early research and development

by Terry Wohlers

The first attempt to create solid objects using photopolymers using a laser took place in the late 1960s at Battelle Memorial Institute. The experiment involved intersecting two laser beams of differing wave length in the middle of a vat of resin, attempting to polymerize (solidify) the material at the point of intersection. The photopolymer resin used in the process was invented in the 1950s by DuPont.

In 1967, Wyn K. Swainson of Denmark applied for a patent titled Method of Producing a 3D Figure by Holography on a similar dual laser beam approach. Subsequently, Swainson launched Formigraphic Engine Co. (Bolinas, California) in hopes to further develop and eventually commercialize his technology. Reportedly, work was still underway in 1994, although it never led to a commercially available system.

In the early 1970s, Formigraphic Engine Co. used the dual-laser approach in the first commercial laser-prototyping project, a process it called photochemical machining. In 1974, Formigraphic demonstrated the generation of a 3D object using a rudimentary system. Later, Formigraphic became Omtec Replication, apparently at a time when an alliance was formed with Battelle (Columbus, Ohio). Dr. Robert Schwerzel, then with Battelle, led the development of similar techniques with the help of DARPA funding. Co-developer Dr. Vincent McGinniss was one of the team members employed by Battelle.

In the late 1970s, Dynell Electronics Corp. was assigned a series of patents on *solid photography.* The invention involved the cutting of cross sections by computer control, using either a milling machine or laser, and stacking them in register to form a 3D object. Dynell merged with United Technologies Corp. in late 1977. As a result, an independent company called Solid Photography was

formed and an affiliated retail outlet named Sculpture by Solid Photography was opened. In mid-1981, Sculpture by Solid Photography changed its name to Robotic Vision. Solid Photography and another company, Solid Copier, operated as subsidiaries of Robotic Vision at least until mid-1989.

Development of stereolithography

Hideo Kodama of the Nagoya Municipal Industrial Research Institute (Nagoya, Japan) was among the first to invent the single-beam laser curing approach, according to several sources. In May 1980, he applied for a patent in Japan, which later expired without proceeding to the examination stage, a requirement of the Japanese patent application process. Kodama claimed to have difficulty in securing funds for additional research and development.

In October 1980, Kodama published a paper titled Three-Dimensional Data Display by Automatic Preparation of a Three-Dimensional Model that outlined his work in detail. His experiments consisted of projecting UV rays using a Toshiba mercury lamp and a photosensitive resin called Tevistar manufactured by Teijin. The method involved black and white film used to mask and control the region of exposure, corresponding to each cross section. The paper also discusses the use of an *x-y* plotter device and optical fiber to deliver a spot of UV light. CMET used a version of this technique in its SOUP 530, 600, and 850 machines.

Kodama published a second paper in November 1981, titled Automatic Method for Fabricating a Three-Dimensional Plastic Model with Photo Hardening.

In *Review of Scientific Instruments*, Kodama describes three basic techniques he used to create plastic parts by solidifying thin, consecutive layers of photopolymer. In the paper, Kodama claims, “If the solidified layer is immersed into the liquid with the top at a depth equal to the thickness of the layer to be solidified, its top surface is covered with unsolidified liquid polymer,” essentially describing a key element of the stereolithography process. Kodama’s experiments with the three techniques were perhaps the first evidence of working additive manufacturing (AM) techniques in the world.

Work in the U.S. and France

In August 1982, Alan Herbert of 3M Graphic Technologies Sector Laboratory published a paper titled Solid Object Generation in the *Journal of Applied Photographic Engineering.* In this paper, Herbert described a system that directs an Argon Ion laser beam onto the surface of photopolymer by means of a mirror system attached to an *x-y* pen plotter device. With the system, Herbert was able to create several small, basic shapes. The primary purpose of the work, however, was to develop an understanding of the requirements of a real system, according to Herbert.

In 1989–1990 timeframe, Wohlers Associates received a handwritten note from Alan Herbert, attached to a copy of his 1982 paper, saying that, unfortunately, his company elected not to commercialize his work. He was apparently very disappointed with 3M’s decision. His interest in the development of AM techniques continued, as indicated by his August 1989 paper titled “A Review of 3D Solid Object Generation” published in the *Journal of Imaging Technology.*

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In July 1984, Jean-Claude Andre, now with the French National Center for Scientific Research (CNRS) in Nancy, France, and colleagues working for the French Cilas Alcatel Industrial Laser Company, filed a patent titled Apparatus for Fabricating a Model of an Industrial Part, involving a single-beam laser approach. The French patent was granted in January 1986. Laser 3D, also of Nancy, France, tried to commercialize the technique outlined in the patent on a service basis with no plans to sell systems.

In the late 1980s, Andre explored the dual-beam approach. He found that many problems existed with it, yet a team at CNRS continued to research the technique. Andre led the development of stereolithography at CNRS for Laser 3D.

Formation of 3D Systems

In August 1984, Charles Hull, co-founder and chief technical officer of 3D Systems (at that time, in Valencia, California), applied for a U.S. patent titled Apparatus for Production of Three-Dimensional Objects by Stereolithography, which was granted in March 1986. At the time of the patent application, Hull was working for UVP, Inc. (San Gabriel, California) as vice president of engineering. In March 1986, Hull and Raymond Freed co-founded 3D Systems Inc. According to Alan Herbert, published illustrations show impressive detailed parts produced by Hull's early system, much more so than those shown by Kodama or himself.

Hull's 1986 patent describes a process of photo-hardening a series of cross sections using a computer-controlled beam of light. Also in 1986, Yehoram Uziel, then of Operatech (Israel) had invented a basic machine resembling stereolithography. Uziel had read about Hull's work, so he traveled to the U.S. to visit him and Ray Freed. In January 1989, he joined 3D Systems as vice president of engineering. In late 1987, 3D shipped its first beta units to customer sites in the U.S., followed by production systems in April 1988. These were the first commercial additive-manufacturing system installations in the world.

Uziel left 3D Systems in 1991 to form Soligen, Inc. (Northridge, California). Around the time Uziel founded Soligen, he licensed MIT's ink jet printing technique for exclusive use in the metal-casting industry. Soligen used MIT's technology in its Direct Shell Production Casting, a process that created ceramic investment casting shells (molds) by adhering together thin layers of ceramic powder material using droplets of liquid binder. Soligen went out of business in 2006.

In 1986, Hull was not the only one with patent activity on his mind. The same year, Takashi Morihara of Fujitsu Ltd. patented two elements of stereolithography. One of them involved passing a blade over the surface of a new layer of resin to speed the leveling of the layer. This technique is especially important when the resin is viscous. For many years, 3D Systems used this leveling technique in its SLA family of stereolithography products. Another approach developed by Morihara involved the dispensing of the resin from a slot moving above the surface of the resin. From early 1990 to early 1992, Quadrax Laser Technologies (Portsmouth, Rhode Island) used this resin deposition technique in its fast resin applicator, a feature contained in its Mark 1000 stereolithography machine.

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Quadrax developed and sold the Mark 1000 system until February 1992, when its technology was acquired by 3D Systems after patent litigation that began in September 1990. Under the terms of the settlement, Quadrax transferred its laser modeling patent (granted in December 1991) and related technology to 3D in exchange for 130,000 shares of 3D common stock. At the time, the stock was worth about $325,000. As part of the agreement, Quadrax was required to discontinue marketing its AM system. Former employees of Laser Fare Ltd. (Smithfield, Rhode Island) developed some of Quadrax's original technology and later became employees of Quadrax. Laser Fare sold the technology rights to Quadrax in 1990.

Osaka Prefectural Industrial Research Institute

In 1984, Yoji Marutani of the Osaka Prefectural Industrial Research Institute (OPIRI), also referred to as the Osaka Institute of Industrial Technology, developed and demonstrated a stereolithography process. It's not clear whether his work was connected with Kodama's early work, although there's a very good chance that Marutani at least studied Kodama's May 1980 patent application and his October 1980 and November 1981 technical papers. It's also possible that Marutani obtained a copy of Herbert's 1982 paper, but it's doubtful that Marutani knew about Hull's and Andre's work in 1984.

Marutani's patent document, titled Optical Molding Method, dated May 23, 1984, describes his invention in detail. The document describes many key elements of stereolithography, including the use of photocurable liquid material, focusing rays of light onto the surface of the liquid resin and presenting a fresh layer of material on top of the hardened layer.

Marutani continued his research and development of stereolithography, at least until mid-1987. In a paper dated August 7, 1987, Takashi Nakai and Yoji Marutani explained that they had developed a new type of system for constructing 3D models using a UV laser and liquid polymer. Rather than discussing the development of a new type of system, however, the paper discusses refinements to already known processes—refinements that increase speed and dimensional accuracy. At the time of publication, both Nakai and Marutani were working in the Department of Electronics at the OPIRI. Kodama's 1981 paper and Herbert's 1982 paper were included as references. It is believed that Marutani is still involved with AM today.

Commercialization of OPIRI technology

OPIRI, operated by the Ministry of International Trade and Industry (MITI), licensed its stereolithography technology to a group of Japanese companies, including Mitsubishi Heavy Industries, NTT Data Communications, Asahi Denka Kogyo, Toyo Denki Seizo, and YAC. Together they formed Computer Modeling and Engineering Technology (CMET) to develop, manufacture, and sell AM systems. The exact licensing date is not known, although Mitsubishi announced in July 1988 that it would sell a stereolithography machine developed jointly with OPIRI. It has been documented that these five companies supported the development and commercialization of the technology in 1989, leading to the introduction of the SOUP system in 1990. A dated SOUP product brochure, published by CMET, states that the "product had been developed on the invention of Osaka Prefectural Industrial Research Institute."

Mitsubishi, with a 54% stake, was responsible for planning and development; NTT Data Communications, with 20%, was responsible for software development; Asahi Denka Kogyo, 20%, photosensitive resins; Toyo Denki Seizo, 3%, development of the *x-y* plotter mechanism and other hardware; YAC, 3%, precision machine manufacturing technology. Mitsubishi Heavy Industries reportedly spent 3 billion yen on further developing the OPIRI technology. At 40–50 million yen per unit, Mitsubishi reportedly sold nine SOUP systems from early 1989 to early 1990.

Sony and Mitsui enter the picture

In 1989, Design-Model and Engineering Center (D-MEC) was launched as a joint venture between Sony and Japan Synthetic Rubber (JSR). In April/May 1989, D-MEC introduced its Solid Creation System (SCS) for 53 million yen. The system was capable of building urethane acrylate resin parts up to 1000 x 1000 x 750 mm in size from layers at thin as 50 microns (0.002 inch). According to one reliable source, the system was developed behind closed doors and details about its origins have been kept quiet. Clearly, Sony had knowledge of OPIRI and CMET's technology, as well as the technology developed by 3D Systems.

3D Systems began to establish a presence in Japan in early 1988 when the company formed a joint venture with Japan Steel Works, Ltd. (JSW), a Mitsui company. 3D executives signed the agreement with JSW in March 1988. The new company, JSW-3D Co., Ltd. (Tokyo), served as a sales, marketing, and service organization for 3D Systems in Japan. SLA machines were made available to the Japanese by the third or fourth quarter of 1988. Near the end of 1989, 3D terminated the agreement and formed a wholly owned subsidiary, 3D Systems Japan.

Mitsui Engineering and Shipbuilding Company announced its COLAMM system in March 1991 and introduced it in July 1991 when it offered a series of introductory seminars. Mitsui's approach to stereolithography is different than the systems from 3D Systems, CMET, and Sony/D-MEC. Rather than building up layers from the top, a laser beam is presented through a transparent plate at the bottom of the build chamber. Each new layer of resin rests between the previously cured layer (which is above the resin) and the transparent plate (which is below the resin). With each new layer, the part moves upward into air space, rather than being submerged in resin.

Mitsui sold one unit to an automobile modeling company in Kyoto in December 1991, but has not reported any sales since then. The company had hoped for sales of 20–30 units in fiscal year 1992. The original COLAMM system, equipped with an engineering workstation, sold for 41 million yen. The company worked with Sanyo Chemical Industries to develop an improved resin with reduced shrink properties.

In January 1989, Mitsui and Nippon Steel announced their plans to form ajoint venture called Plamedia Research Corp. The company would design and develop metal molds for producing parts made from plastics. It's not clear whether this venture was related to the development of Mitsui's AM system.

The June 92 issue of *Jetro* explains Mitsui's AM approach, verbatim, as a recent invention by professors N. Nakajima and T. Takagi of the Faculty of Engineering, University of Tokyo. According to the article, the process can

build mechanical parts with 8-micron (0.00032-inch) features at an accuracy of ±1 micron (0.00004 inch). Yet the article does not mention the Mitsui COLAMM system.

Teijin Seiki enters with DuPont's help

In 1989, DuPont announced the development of its Somos 1000 Solid Imaging System, a technology similar to 3D Systems' SLA. Because of their similarities, DuPont petitioned the U.S. Patent Office in September 1988 for a reexamination of Hull's 1986 patent. DuPont made the Patent Office aware of Kodama's publications, as well as those of others. Seven months later, the Patent Office told 3D Systems that it had rejected all claims in Hull's patent. This was about the time DuPont chose to go public with its Somos system, which occurred around June 1989. In late 1989, the U.S. Patent Office reversed its decision after 3D Systems produced strong evidence to support the claims in Hull's patent, but required the addition of new language that narrowed its scope. This was a turning point for DuPont.

Teijin Seiki acquired DuPont's Somos stereolithography technology through a licensing agreement in late 1991. In March 1992, at the Optomechatronics Show '92, Teijin Seiki announced the availability of its Soliform AM system for 50 million yen. The machine was an enhanced version of DuPont's original Somos system, according to Teijin Seiki. With its impressive laser draw speed of up to 2,400 cm (945 inches) per second, the company considered it a second-generation AM system. Teijin Seiki had introduced two versions of its Somos technology, the Soliform 300 (300-mm build chamber) and the Soliform 500 (500-mm), and had made them available for sale in Asia.

Teijin Seiki obtained the exclusive rights to manufacture and sell DuPont's Somos technology, although it was limited to Asia. The Japanese company paid approximately 700 million yen to obtain the license, including the system's blueprints, operating knowledge, and patent and sales rights. After securing the Somos technology, Teijin Seiki moved 10 researchers from the electromechanical development department of its Iwakuni plant to it Kanagawa Science Park laboratories to work on the Somos project. In 1991, Teijin projected annual sales of 10 billion yen in 3–4 years.

In 1989, DuPont filed several patent applications related to stereolithography. Four of them concentrated on photopolymer developments. In the mid 1990s, DuPont supplied resins to Teijin Seiki, Electro Optical Systems (Germany), and users of 3D Systems' SLA 250 and SLA 500 models.

Others jump in

In early 1989, Hans J. Langer, formally of General Scanning (German branch), and a few associates started Electro Optical Systems (EOS). By mid-1990, BMW ordered its first system from EOS, and later a second for about DM 1 million. European Technology Holding, a venture capital company in Amsterdam, provided the basic financial support for Langer to go into business. Langer also secured DM 1 million from the German Federal Government's program for young technology entrepreneurs. Between mid-1991 and July 1993, EOS had shipped 15 STEREOS stereolithography systems to sites in Europe and Japan. Another customer, Hitachi Zosen Information Systems, had begun to market the EOS system in Japan.

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In 1991, Nissei Sangyo Company announced the availability of an AM product, a combination of elements from Matsuo Sangyo and 3D Systems Japan. During the first year, Nissei Sangyo expected to sell 15 units, priced at about 100 million yen. Little is known about this development.

In early 1993, Denken Engineering (Oita City, Oita Pref., Japan) and Autostrada Corp. jointly introduced a 7.8 million yen stereolithography system called the Solid LD Plotter System, SLP-3000. The unit uses visible light and a laser diode, rather than expensive lasers used in other stereolithography systems. According to Denken, the overall size of the SLP-3000 is small compared to competitive systems, yet it is capable of producing parts up to 200 x 400 x 300 mm (about 8 x 16 x 12 inches). The company hoped to sell about 50 units per year, many going to Japanese government labs.

Non-stereolithography approaches

While the Japanese concentrated on the stereolithography process, companies and individuals in the U.S. and Israel were developing other approaches to additive manufacturing.

In June 1986, Itzchak Pomerantz, founder and former president of Cubital (Raanana, Israel), filed for an Israeli patent. At the time, Pomerantz was working for Scitex Corporation, an Israeli company that owned a small percentage of Cubital. Pomerantz' patent, titled Three-Dimensional Mapping and Modeling System, laid the ground work for the Solider 5600, which Cubital introduced in July 1987. In May 1988, Cubital and 3D Systems cross-licensed certain parts of their technologies to minimize the possibility of subsequent legal conflicts.

In 1986, Russian immigrant Dr. Efrem Fudim of Light Sculpting (Milwaukee, WI) offered one of the first commercially available part-building services using an AM technology he invented. His system projects a flood of light from a UV lamp through a mask onto the surface of photopolymer. This mask approach was similar to Cubital's photo mask, although Cubital had automated the process. With Fudim's system, individual masks were produced on a Gerber photoplotter and manually positioned over the build chamber for each new layer. This labor intensive, time-consuming approach did not win the hearts of buyers. Consequently, Fudim did not sell a single system.

Missing from Fudim's machine was a fast way to transfer the cross section information to the build chamber. In October 1991, Sanyo Electric applied for a patent involving a flat LCD panel as a mask through which UV light would shine onto the surface of photopolymer. Tests, however, indicated that the UV light would deteriorate the liquid crystal, shortening its effectiveness to hours. Fudim had also considered this approach.

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