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A Novel Device for Producing Three-Dimensional Objects

This work describes a novel device for producing three-dimensional objects that has been developed using a liquid crystal display as a programmable, dynamic mask and visible light to initiate photopolymerization. This device has the potential to produce three-dimensional objects of comparable quality to the existing commercial devices, but in significantly less time. Additionally, capital, maintenance and operating costs are expected to be substantially lower than those for laser-based systems. The reduction in time and expense could expand this technology into the realm of custom part production and further increase the accessibility and usefulness of solid freeform fabrication and rapid prototyping.

Introduction

Life-size three-dimensional (3-D) prototypes are used in a wide variety of industries to facilitate the development of new products. Solid freeform fabrication (SFF) technology has been used to design non-custom hip implants along with radio parts, ski bindings, car parts and numerous other devices (Jacobs, 1992; Blake and Baumgardner, 1992; Schmidt and Phillips, 1992; Kerschensteiner, 1992; Trimmer, 1992; Bill et al., 1995). Applications of SFF are increasing dramatically, which means that improvements to existing techniques will have a tremendous impact on product development time and cost. If the cost barrier can be lowered sufficiently, SFF will be a powerful tool for custom part fabrication.

Original methods of prototype production were labor and material intensive and have historically represented a significant fraction of new product development costs. In the 1980's, researchers began developing alternative rapid prototyping methods that capitalized on the spatial resolution and control of photopolymerizations (Herbert, 1982; Kodama, 1981; Hull, 1986; Fudim, 1986). For example, one method involved placing a mask over a thin layer of light sensitive resin and then irradiating the resin through the mask with ultraviolet (UV) light (Fudim, 1986). The resin polymerized only where light penetrated, thus creating an image of the mask. The masks were made of Mylar film or glass. A limitation of this method was that complex 3-D objects might require hundreds of different masks to achieve the desired resolution of the part. An alternative technique, stereolithography (SL), is currently the most prominent and effective means of producing 3-D objects from photosensitive resins (Hull, 1986). In the most common embodiment of the SL process, a platform is placed in a vat of light sensitive resin. The first layer is built on the platform using a UV laser to polymerize thin lines of resin according to the computer-aided-design (CAD) drawing for that layer. Once the first layer is complete, the platform is lowered into the vat; a fresh layer of resin covers the surface; and the next layer of the object is polymerized. The 3-D structure is built layer-by-layer through repetition of this process.

Several other innovative strategies have been developed for producing three-dimensional objects. A three-dimensional modeling apparatus (Pomerantz et al., 1990) generates erasable masks through electrophotographic techniques. Photochemical machining (Fallon, 1989; Belforte, 1989) uses intersecting lasers to selectively crosslink a block of polymer or degrade and remove material from a solid block. Laminated object manufacturing (Belforte, 1989; Fallon, 1989; Klosterman et al., 1997; Studt, 1994) uses a CO_2 laser to cut each layer pattern into sheets of material that are thermally adhered to the previous layer. Ballistic particle manufacturing (Fallon, 1989; Hauber, 1988) produces metal objects by directing particles at a target. The object is built-up in layers through cold welding. Directed light fabrication (Studt, 1994) produces metal parts through fusion of metal powders at the focal point of a Nd:YAG laser. Selective laser sintering (Nelson et al., 1995; Studt, 1994; Belforte, 1989; Fallon, 1989) fuses powdered thermoplastic materials using an infrared laser. Three-dimensional printing (Sachs et al., 1992) uses "ink jet" printing to selectively bind ceramic, metal or polymeric powders into solid parts. Microstereolithography (Bertsch et al., 1997) is similar to this work in that it uses a liquid crystal display (LCD) as a dynamic mask to photopolymerize entire layers. The configuration of the device uses a vat of photopolymer just as in stereolithography. There are drawbacks associated with using vats of photopolymer, which are avoided using our device. Direct Photo Shaping (Ventura et al., 1996) also uses an LCD as a dynamic mask to form objects from slurries of ceramic powders and photocurable monomers. Their device polymerizes from the top and creates the object in a large cube from which excess material is removed once the build is complete.

The existing SL systems have been improved dramatically since their initial conception and their performance is quite impressive. Despite this achievement, there is still room for improvement. Desirable enhancements to the SL process are increased accessibility of the technology by reducing the costs of acquisition, maintenance and operation. Decreased build times are also very important along with flexibility in the choice of resin. This work describes a novel device, which is under development in our laboratory for producing 3-D objects. This device is based on using a liquid crystal display (LCD) as a programmable, dynamic mask and an initiating system that is sensitive to visible light. The build-time is independent of cross-sectional area and thus the required build time has been significantly reduced for most objects. Since this is not a laser-based system, the light source is much cheaper to purchase and maintain. The configuration of this device significantly reduces the resin inventory required. Additionally, resolutions on the order of those achieved by commercial SL systems are achieved using inexpensive off-the-shelf materials.

Experimental Section

The monomer used in this work was dipentaerythritol pentaacrylate (DPPA; Polysciences) and was used as received. This

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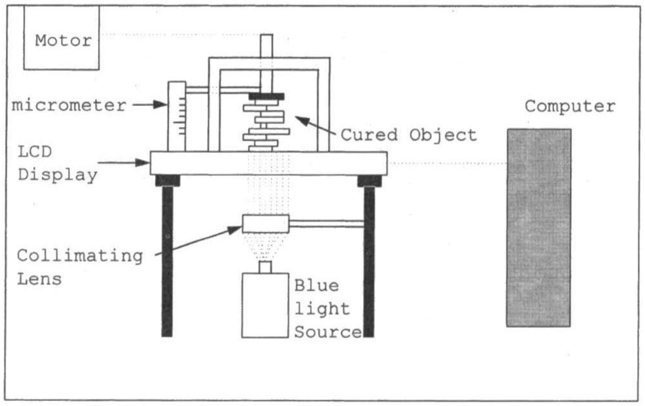

Fig. 1 Novel device for 3-D prototyping or custom part production

viscous multifunctional monomer polymerizes rapidly in the presence of oxygen to form an highly crosslinked polymer with a tensile modulus exceeding 1 Gpa. This acrylate monomer was chosen for its high reactivity and easy handling properties; however, other monomers may be used depending on the desired final material properties. The initiating system was composed of equal weight percents of camphorquinone (CQ; Aldrich) and ethyl 4-dimethylaminobenzoate (EA; Aldrich).

The device is illustrated in Fig. 1. The device consists of an LCD (Sharp QA-50, pixel size 0.09 mm^2) which is interfaced to a computer (Gateway 2000, P5-200). Microsoft PowerPoint© or Paint© is used to create an image on the LCD. A lift device for positioning a platform is placed on top of the LCD. The position of the platform is determined using a micrometer attached to the lift. Blue light (Den-Mat Marathon Two) illuminates the mask from below through a collimating lens (Edmund Scientific). The light intensity at the top surface of the LCD is approximately 1 mW/cm^2. Light intensity was measured using a Cure-Rite radiometer (EFOS), which is sensitive to light between 400 and 500 nm in wavelength. Alternatively, the mask is illuminated using a standard overhead projector (3M).

The 3-D object is created layer-by-layer by placing a small amount of resin under the platform, lowering the platform to the desired height above the LCD, and illuminating the resin for a given amount of time. The illumination time can vary between the time required for the onset of gelation (which allows adhesion between layers) to the time required for full conversion. The newly formed layer is released from the LCD surface; new resin is put in place; the mask is updated; and the next layer is formed. Complex 3-D objects can be built by repeating this process for the number of layers required. If less than full conversion is achieved, then the part can be post-cured.

Results and Discussion

Important issues in 3-D prototyping are resolution, minimum feature size, and build time. Using off-the-shelf acrylate monomers and a common initiating system, our LCD based device has proven capable of rapidly producing objects with the desired geometrical features with good resolution. Figure 2 is an example of a 1 mm thick layer. This layer was created using 2 wt% EA/CQ initiator in DPPA and was completely polymerized in 50 seconds. A higher intensity light source has subsequently reduced the polymerization time to 18 seconds. The root-mean-square (RMS) error for our device is on the order of 0.08 mm. The commercially available SL systems have an RMS of about 0.06 mm using epoxy based resins and 0.1 mm using acrylates (Pang, 1996). RMS is defined as the error range within which 68 percent of the part dimensions will fall given a Gaussian distribution of the error.

The ability to reproduce an object with the exact dimensions required is a strong function of volume shrinkage. Volume shrinkage occurs when the volume of the solid polymer is less than the volume of the initial resin. For acrylates, volume shrinkage is about 22.5 cm^3/mol of double bonds (Patel et al., 1987). This device has better resolution than commercial SL systems when acrylates are used for several reasons. First, using an LCD-based device, the area to be polymerized is continuously exposed to light. Thus, as the polymer shrinks, unreacted resin can move into the exposed area and fill in the voids. Figure 3 illustrates the effect of increased exposure. In contrast, the SL system polymerizes a single point at a time, creating lines with widths proportional to the spot width. The line width and depth are very sensitive to laser power and the resin characteristics. If these parameters are not well controlled then the line width and depth of polymerization will differ from the intended measurements, resulting in lower resolution parts.

A second feature of the LCD-based device that affects resolution is that the entire layer is polymerized uniformly. As a result, adhesion to the prior layer will occur simultaneously everywhere. Thus, distortions associated with one part of the layer attaching and contracting nonuniformly are eliminated. In addition, the LCD-based device can achieve higher conversions during the build step with little increase in time compared to the point-by-point systems. As a result, conversion during post-cure and the associated distortion is minimized. If post-cure is performed by irradiating with a UV source, distortion can occur due to unequal shrinkage rates at varying distances from the source (Jacobs, 1992; Jacobs, 1992).

On the contrary, for commercial SL systems, the drawing method determines the conversion during the build and also the timing for adhesion between layers. Low conversion during the build phase reduces build time but increases the conversion required during the post-curing step. Alternatively, high conversions during the build can cause distortion due to interlayer stresses that occur once the new layer adheres to the previous layer. This problem is somewhat mitigated by making two complete passes across the layer. The first pass cures to within 0.025 mm of the required layer thickness so no adhesion occurs (Jacobs, 1992). The second pass increases the depth of cure so that adhesion occurs. The success of this technique depends greatly on the quality of the resin. If the vat is refilled often, the resin properties can shift causing delamination of parts if underpolymerized or significant distortion if overpolymerized.

A major breakthrough to reduce volume shrinkage during polymerization in the commercial SL systems was achieved by the development of epoxy monomers. Epoxy monomers can polymerize cationically through a ring opening mechanism, thus eliminating the volume shrinkage associated with conversion of double bonds to single bonds (Pang, 1996). However, these zero-shrinking monomers are reasonably expensive compared to their acrylate counterparts. An alternative resin system is a mixture of epoxies

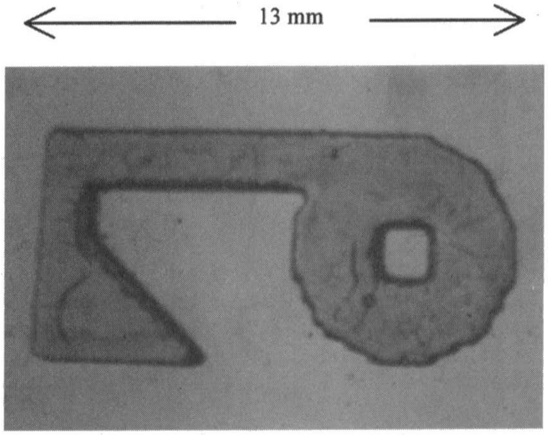

Fig. 2 Single layer object created using LCD based device

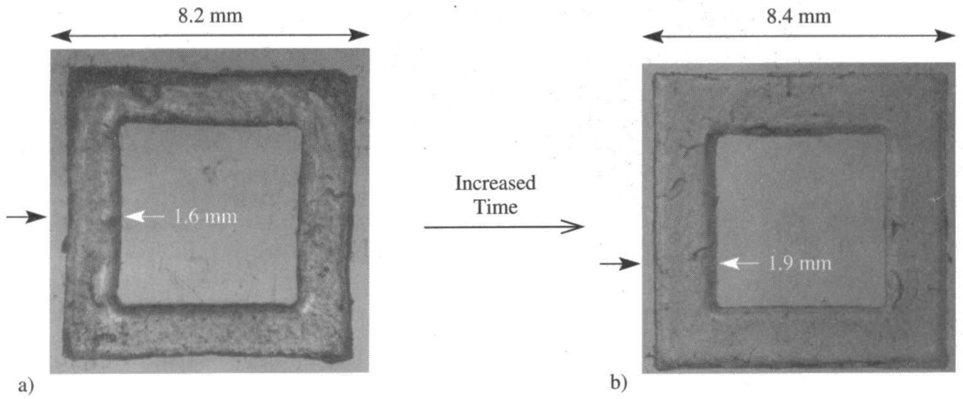

Fig. 3 Effect of polymerization time on reproduction of image. Sample was 0.5 wt% EA/CQ in DPPA and 1 mm thick. The mask was a hollow, straight-edged square. *a*) Polymerization time was 45 seconds and the sides are slightly bowed, *b*) polymerization time was 70 seconds and the sides are now straight. The dimension changes indicated on the drawing were the same for all for sides.

and vinyl ethers. The vinyl ethers polymerize rapidly to form a strong structure while the epoxies remain incompletely cured. The epoxy can then be thermally post-cured, with little distortion, to complete the part (Lapin et al., 1995). The LCD-based device could also take advantage of these new monomers, which will improve the resolution even further.

A third feature of the LCD-based device that contributes to improved resolution is the fact that the object is not built in a vat of resin. Thus, distortion due to swelling of the object does not occur. Additionally, if an object is built in a vat of resin, thin walls or fragile features can be distorted.

There are several operating conditions that affect the resolution of the object and the polymerization time of a layer. Contrast between light and dark areas on the LCD and light intensity affect the resolution in the horizontal plane. We have found that there is a maximum light intensity that can be used for a given contrast on the LCD. If the light intensity is higher than the maximum, then polymerization occurs outside the desired region before the desired layer thickness is achieved. As the contrast between light and dark regions is increased, the light intensity can be increased. To minimize polymerization time, one would want to use the maximum light intensity possible. However, a tradeoff exists between rapid rates of polymerization and the resolution of the object. If the rate of polymerization exceeds the rate of volume shrinkage, then volume shrinkage will continue after the light is turned off (Kloosterboer, 1988), causing slight distortions in the object. Vertical resolution is controlled by the layer thickness of monomer on the surface of the device.

The effect of initiator concentration on polymerization time for 1 mm thick samples has been studied. The optimum initiator concentration in terms of minimum time, for this system is 2 wt% each of EA and CQ. Polymerization time decreased from six minutes to 20 seconds as the initiator concentration was increased from 0.1 wt% to 2 wt%. Above 2 wt%, polymerization time increases due to light attenuation which results in significantly lower light intensities at the top of the layer. Increased layer thickness has the same effect; as layer thickness increases, the time required to complete polymerization per increment of thickness increases non-linearly. At some point, the layer will be so thick that light does not penetrate through to the topside and no adhesion to the prior layer will occur.

The polymerization time is also a function of the conversion required. The minimum amount of time is determined by the requirement that each layer must adhere to the prior layer. Polymerization times beyond the minimum serve to increase conversion. Depending on the object features, it may be sufficient to simply obtain adhesion between layers and post-cure the object later. However, if the object is somewhat fragile, it would be advantageous to achieve maximum conversion as it is built. Thus, there are several factors and adjustable parameters that determine the build time required for any given object.

Feature size is another important issue. For our LCD based device, the smallest feature size is limited by the size of the pixels. Figure 4 illustrates that one-pixel differences are clearly distinguishable. We have also succeeded in producing a multilayer object with a 1 × 1-pixel tunnel throughout the object. The pixel size on our off-the-shelf LCD is about 0.3 mm which compares favorably with the laser-based systems. In a laser-based system, the smallest feature size producible is related to the beam diameter. The line width produced varies effectively between 0.7 and 1.4 times the beam diameter depending on the laser velocity and properties of the resin. For a 0.2 mm beam diameter, the line width will be between 0.14 and 0.28 mm. At the same time, however, the depth of cure is also affected. If the same laser spot size is used, smaller line widths are drawn by increasing the laser velocity. If the line width is cut in half, the cure depth is reduced by a factor of 4, which quadruples the number of layers that must be built. Even though the laser velocity is significantly faster, there is substantial time involved in repositioning the object under the resin surface. Thus, the overall build-time will at least double and perhaps increase by larger factors depending on the part.

A compelling reason for pursuing the development of this device is the significant reduction in build-time. A 6 × 6 × 0.25 inch slab takes about 1.3 hours to build using the commercially available device. Using the LCD-based device, this same object can be built in about 12 minutes. Significantly reduced build times open up numerous possibilities for rapid production of custom made parts in addition to reducing prototyping times.

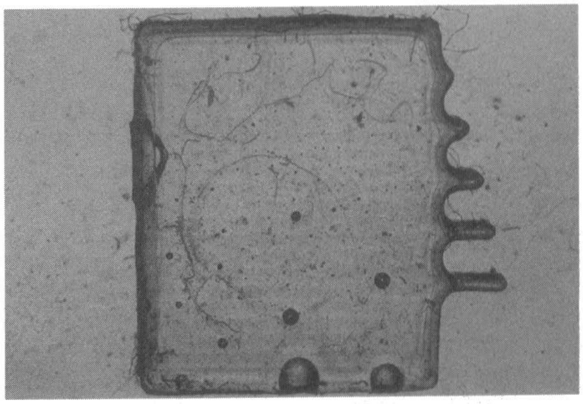

Fig. 4 Projections are incremented in size from top to bottom by 1 pixel and are 1 pixel wide

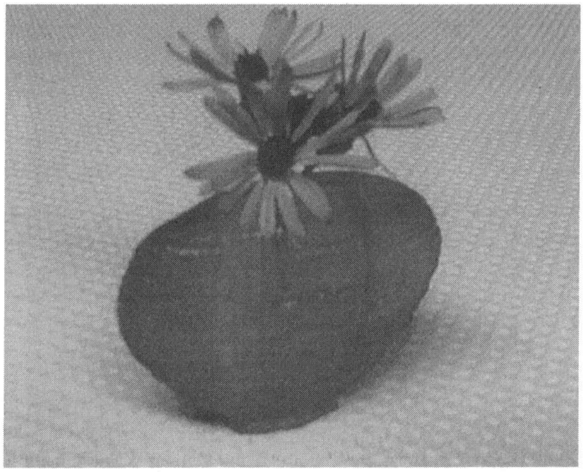

Fig. 5 Hollow vase created using novel device. Vase consisted of 82 layers that were 0.5 mm thick. Microsoft PowerPoint© was used to create the masks for each layer.

For example, one could envision producing custom orthopedic implants based on MRIs in a hospital environment.

The build-time is directly impacted by the method used to create each layer. The SL process uses a layer-additive, laser point-by-point fabrication method. It is layer-additive because multiple layers are used to build-up the object, and it is point-by-point because the laser is illuminating only a small spot (0.2 to 0.3 mm in diameter, 3D Systems SLA specifications) at any instant in time. Due to the point-by-point nature of this process the time required to build each layer is directly proportional to the cross-sectional area of the layer. To bypass this limitation, thicker layers might be proposed; however, thicker layers decrease the resolution in the vertical direction. In addition, the time required to polymerize a layer increases non-linearly with layer thickness due to attenuation of light intensity according to Lambert-Beer's law. Thus, a process that polymerizes the entire area at one time will have significantly shorter build-times for most geometries.

Other considerations in the development of a new device are the purchase, maintenance and operating costs. We expect the costs for acquiring, maintaining and operating this device to be significantly smaller than those of laser-based SFF systems. Much of this expectation stems from the lower purchase and maintenance cost of a non-laser visible light source. Additionally, the sophisticated optics and laser beam positioning hardware and software are unnecessary.

Figure 5 illustrates a three-dimensional object that was fabricated with this device. Because new resin is added between layers, each layer can be formed from a different material. Thus, objects can be produced with varying material properties within the object. For example, the object could be a combination of flexible and inflexible parts. Different layers could be various colors. Fillers could be used in one portion and not another. If a biodegradable object were produced, the degradation characteristics could be tailored by changing the composition of the layers as the object is built.

We have not fully explored the realm of part geometries that can be fabricated with this device. Clearly, objects with gradual changes in the horizontal direction can be fabricated. Large shelves will be more challenging. In commercial SL systems, supports are built along with the part. This may be unavoidable for this device as well. Hollow objects are more easily fabricated with the LCD-based device because the part is not immersed in monomer.

Conclusion

A novel device for three-dimensional prototyping or custom part fabrication has been developed that has the ability to rapidly produce complex objects with good resolution and varying material properties and characteristics throughout the object. This device has advantages over the existing commercial devices in that it is expected to be much less expensive to acquire, maintain and operate. The lower cost and reduced production time increases the accessibility and thus the number of users and applications of solid freeform fabrication technology.

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References

Belforte, D. A., 1989, "Laser Modeling Reduces Engineering Time," *Laser Focus World*, Vol. 25, pp. 103–108.

Bertsch, A., Jezequel, J. Y., and Andre, J. C., 1997, "Study of the Spatial Resolution of a New 3D Microfabrication Process: The Microstereophotolithography Using a Dynamic Mask-Generator Technique," *Journal of Photochemistry and Photobiology. A, Chemistry*, Vol. 107, pp. 275–281.

Bill, J. S., Reuther, J. F., Dittmann, W., Kubler, N., Meier, J. L., Pistner, H., and Wittenberg, G., 1995, "Stereolithography in Oral and Maxillofacial Operation Planning," *International Journal of Oral and Maxillofacial Surgery*, Vol. 24, pp. 98–103.

Blake, P., and Baumgardner, O., 1992, "Texas Instruments: An Aerospace Case Study," *Rapid Prototyping & Manufacturing: Fundamentals of Stereolithography*, Society of Manufacturing Engineers, Dearborn, Mich.

Fallon, M., 1989, "Desktop Manufacturing Takes You From Art to Part," *Plastics Technology*, Vol. 35, pp. 78–82.

Fudim, E. V., 1986, "Sculpting Parts with Light," *Machine Design*, Vol. 58, pp. 102–106.

Hauber, D., 1988, "Automatic Production of P/M Parts Directly From a Computer Aided Design Model," *The International Journal of Powder Metallurgy*, Vol. 24, pp. 337–342.

Herbert, A. J., 1982, "Solid Object Generation," *Journal of Applied Photographic Engineering*, Vol. 8, pp. 185–188.

Hull, C. W., 1986, "Apparatus for Production of Three-Dimensional Objects by Stereolithography," U.S. Patent No. 4,575,330.

Jacobs, P. F., 1992, "Advanced Part Building," *Rapid Prototyping & Manufacturing: Fundamentals of Stereolithography*, Society of Manufacturing Engineers, Dearborn, Mich.

Jacobs, P. F., 1992, "Postprocessing," *Rapid Prototyping & Manufacturing: Fundamentals of Stereolithography*, Society of Manufacturing Engineers, Dearborn, Mich.

Kerschensteiner, T. A., 1992, "AMP Incorporated: A Simultaneous Engineering Case Study," *Rapid Prototyping & Manufacturing: Fundamentals of Stereolithography*, Society of Manufacturing Engineers, Dearborn, Mich.

Kloosterboer, J. G., 1988, "Network Formation by Chain Crosslinking Photopolymerization and its Applications in Electronics," *Advances in Polymer Science*, Vol. 84, pp. 1–61.

Klosterman, D., Chartoff, R., Osborne, N., and Graves, G., 1997, "Laminated Object Manufacturing, A New Process for the Direct Manufacture of Monolithic Ceramics and Continuous Fiber CMCs," *Ceramic Engineering and Science Proceedings*, Vol. 18, pp. 113–120.

Kodama, H., 1981, "Fabrication of 3-D Plastic Models," *Review of Scientific Instruments*, Vol. 52, pp. 73–76.

Lapin, S. C., Snyder, J. R., Sitzmann, E. V., Barnes, D. K., Green, G. D., 1995, "Stereolithography Using Vinyl Ether-Epoxide Polymers," U.S. Patent No. 5437964.

Nelson, J. C., Vail, N. K., Barlow, J. W., Beaman, J. J., Bourell, D. L., and Marcus, H. L., 1995, "Selective Laser Sintering of Polymer-Coated Silicon Carbide Powders," *Industrial & Engineering Chemistry Research*, Vol. 34, pp. 1641–1651.

Pang, T. H., 1996, "Advances in Stereolithography Photopolymer Systems," *Stereolithography and Other RP&M Technologies: from Rapid Prototyping to Rapid Tooling*, Society of Manufacturing Engineers, Dearborn, Mich.

Patel, M. P., Braden, M., and Davy, K. W. M., 1987, "Polymerization Shrinkage of Methacrylate Esters," *Biomaterials*, Vol. 8, pp. 53–56.

Pomerantz, I., Cohen-Sabban, J., Bieber, A., Kamir, J., Katz, M., Nagler, M., 1990, "Three Dimensional Modelling Apparatus," U.S. Patent No. 4,961,154.

Sachs, E., Cima, M., Williams, P., Brancazio, D., and Cornie, J., 1992, "Three Dimensional Printing: Rapid Tooling and Prototypes Directly from a CAD Model," ASME JOURNAL OF ENGINEERING FOR INDUSTRY, Vol. 114, pp. 481.

Schmidt, L. D., and Phillips, W. L., 1992, "Chrysler Corporation: An Automotive Case Study," *Rapid Prototyping & Manufacturing: Fundamentals of Stereolithography*, Society of Manufacturing Engineers, Dearborn, Mich.

Studt, T., 1994, "Rapid Prototyping Key to Fast Development," *R&D*, Vol. 36, pp. 55–56.

Trimmer, D. G., 1992, "DePuy, Incorporated: A Medical Case Study," *Rapid Prototyping & Manufacturing: Fundamentals of Stereolithography*, Society of Manufacturing Engineers, Dearborn, Mich.

Ventura, S. C., Narang, S. C., Sharma, S., Stotts, J., Liu, C., Liu, S., Ho, L., Annavajjula, D., Lombardo, S. J., Hardy, A., Mangaudis, M., Chen, E., and Groseclose, L., 1996, "A New SFF Process for Functional Ceramic Components," *Proceedings Solid Freeform Fabrication*, D. L. Bourell, eds., University of Texas, Austin, TX, pp. 327–334.