SOLID FREEFORM FABRICATION AND SELECTIVE POWDER SINTERING

by

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ABSTRACT: Solid freeform fabrication, a concept for a new class of processes which are three-dimensional analogies to dot matrix printing, is presented. The objective of these processes is to produce freeform solid objects directly from a computer model without part-specific tooling or human intervention. Several concepts for implementation of solid freeform fabrication are also presented. Development of one of these processes, Selective Powder Sintering, is being conducted at The University of Texas at Austin. Selective Powder Sintering produces objects in layers from a powder by selectively sintering with a laser. Initial experimental results are encouraging and three-dimensional objects are being produced.

Introduction

The cost of manufacturing a particular mechanical component is a direct function of the production quantity of that component. Conventional automated manufacturing technologies are well suited to the manufacture of large production numbers but are ill suited to the manufacture of low production numbers of a particular component. This is due to the need to amortize the cost of part specific hardware and/or software over a large number of components. As a result, the manufacture of low production number mechanical components is done mainly by manual methods which leads to a substantially higher unit cost for these components.

Even with manual methods using standard machines and standard tools there is an investment in part specific knowledge. It takes the machinist or other craftsman time to figure out how to manufacture the part, how to clamp it, what tools to use, what machine to use, what order to do the cuts in, what feeds and speeds to use. The cost of set-up time must also be considered. For these reasons, low production number mechanical components are much more expensive than the same component would be in mass production. This is especially true for prototype parts for one-of-a-kind parts. This situation is even more pronounced for mechanical components that are designed to be cast, molded, or otherwise produced with a process that transfers the shape of a part specific tool to the component because of the complex shapes and compound curves often found.

Printing is a good two-dimensional analogy to this problem. Lettering or drawing by hand is analogous to manual manufacturing methods. Offset printing is analogous to modern automated manufacturing techniques. One method of printing that does not have an analogy in manufacturing is dot matrix printing (or laser printing). Dot matrix printing can produce any two-dimensional pattern on paper directly from a computer with resolution being the only restriction. Dot matrix printing cannot compete with offset printing for large numbers of copies, but is very practical for small numbers of copies. It's usefulness can be extended by using it as an input to other processes such as photocopying.

This analogy illustrates an opportunity for a manufacturing technology that produces freeform solid objects directly from a computer model of the object without part-specific hardware, software, or knowledge in a way that is a three-dimensional analogy to dot matrix printing. Such a process would not need to be able to compete with conventional processes for the production of large production numbers, but would only need to compete in low production number situations such as the production of prototype parts, design visualization models, and casting patterns. Such a process would be useful if it could produce solid shapes with reasonable tolerances, even if the material properties were inferior to those achievable with conventional processes because secondary processes such as investment casting (lost wax casting) can be used to go from a low strength pre-form with the correct shape to a higher strength component with the same shape.

The problem of creating such a manufacturing process can be broken into two parts: 1) find a format that can represent all three-dimensional shapes, and 2) create a process that can manufacture three-dimensional solid objects directly from that format with a minimum of constraints. The difficulty lies in the infinite number of three-dimensional freeform shapes.

Representation

One way to represent three-dimensional freeform shapes is to extend the idea of dot matrix printing and raster computer graphics to three dimensions. Consider a cube in space. Now divide each edge of the cube into 256 equal segments. Now consider the 256 x 256 x 256 array of small cubes created. Call these smaller cubes voxels, which is short for volume element and is the three-dimensional counterpart to the two dimensional pixel or picture element.

Now assume that we can dictate the state of each voxel independently. The state of each voxel is a one or a zero, with one corresponding to having a solid occupy the voxel and zero corresponding to an empty voxel. We can now describe any freeform three-dimensional shape that falls within the large cube only being restricted by the resolution.

Fabrication

Once we represent the shapes in terms of an array of voxels, then it is desirable to manufacture the shape from this representation without constraints. If one aspect of the shape of the component dictates other aspects of the shape, then this is a constraint. An example is the production of a component with an internal void by conventional machining as shown in Figure 1. In order to cut away the material originally occupying the region A, the material originally occupying region B must be removed so that the tool may have access to region A. This coupling of the state of the region A and the state of region B is a constraint and is a function of the geometry of the cutting tool. Constraints such as this make it necessary to consider the three-dimensional component as a whole instead of considering each voxel of the component separately. In general, making decisions which must take into account the geometry of the object as a whole will require human intervention.

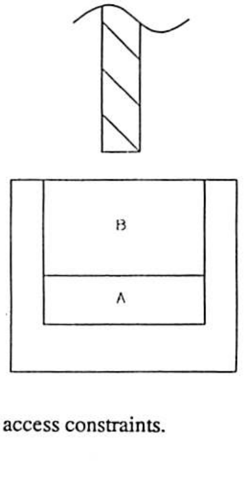

Figure 1: Example of access constraints.

For this reason conventional material removal processes are not appropriate for manufacturing components directly from the voxel model without human intervention. One way to avoid this problem is to build the component in thin layers by material addition. Each layer would be one voxel thick and would correspond to a particular cross-section of the component. In this way the problem of access constraints is eliminated because the operation on the part is always occurring on the surface. No human intervention is required because each voxel of the component is dealt with individually instead of dealing with the entire object as a whole. If the component is to be built in layers, then it is natural to represent the three-dimensional array of voxels as a set of two-dimensional arrays of voxels. One way to produce a two-dimensional pattern from the voxel representation is to use a raster strategy.

What is needed is an additive process that will be able to build up general shaped two-dimensional patterns on the previously built up layers using a raster strategy. This concept of fabricating freeform solid objects by repetitive addition of thin layers in a raster fashion is called Solid Freeform Fabrication (SFF). Several process concepts that could be used are as follows:

1. Dot matrix wire arc welding: A micro-wire welder is raster scanned over a substrate and selectively welds a two-dimensional pattern. Each time the welder is over a voxel that should be occupied by the object, an arc is struck and a small volume of metal is deposited. This process is repeated for each layer. Alternately, an entire line is welded at a time in the fashion of a line printer or an entire layer in the fashion of a page printer. Objects have been built up by repetitive wire welding in a vector fashion as in [1].

2. Dot matrix extrusion: An extrusion head is fashioned that can extrude a small volume of material selectively under the control of a small valve. The head is raster scanned as described for the dot matrix welding approach. Alternatively, entire lines or pages are extruded.

3. Raster droplet spray: Droplets of molten material or partially cured thermoset plastic material would be selectively applied to the surface in a stream guided by electrostatic deflection in the same way as water droplets are guided in a cell sorter or in a way similar to an ink jet printer.

4. Photochemical methods: A layer of photo hardening liquid would be selectively hardened by a raster scanning UV laser beam. This could be done with one beam acting on the surface with liquid being added after each layer or this could be done under the surface with two or more crossed beams and a liquid that has a sharp threshold. In the second case, the liquid would need to be transparent to the beam and the liquid would be in place several layers in advance. Alternately, sheets of photo resist could be used.

These methods were conceived independently by Charles Hull of UVP, Inc. of San Gabriel, Ca. and are being developed under the name Stereolithography [2] (see Figure 2).

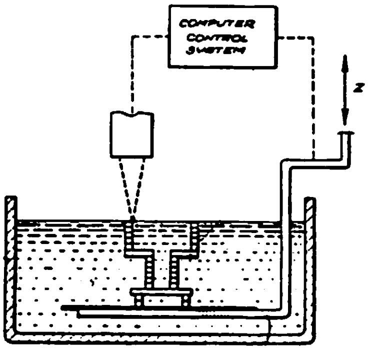

Figure 2: Stereolithography [2]

5. Cut sheet method: A thin sheet of material could be applied to the sum of the previous layers and be adhered by heating. The sheet would then be allowed to cool, then be trimmed with a laser, and the excess would then be removed with a vacuum cleaner. This concept does not use a raster strategy.

6. Binary powder method: Lay down a layer consisting of two different powders in a pattern in the fashion of an American Indian sand painting. The first powder would have a significantly lower softening temperature or sintering temperature than the second. Build these layers up in a container until you have the first powder in the shape of the desired component supported by the second powder. Then heat the entire container of powder to a temperature between the two softening points causing the first powder to flow together or sinter while being supported by the second powder.

7. Selective powder sintering (SPS): Lay down a homogeneous layer of powder and selectively sinter or melt with a laser beam or other energy beam. The unaffected powder would remain in place to support the next layer of powder. This concept would work with any powder that can be melted or sintered with a laser including metal powders. Other methods of selective energy application (example, heat bar as in thermal transfer printing or line of small plasma jets) can be used.

Layerglaze, a process developed by United Technologies Research Labs, built up objects by repetitive laser welding of a superalloy powder in a vector fashion [3]. The objective was novel material properties due to rapid solidification. This project was primarily interested in the production of turbine rotor blades. Production of near net shape objects was proposed. (see Figure 3). Thermal stress was a major problem and the project has been terminated.

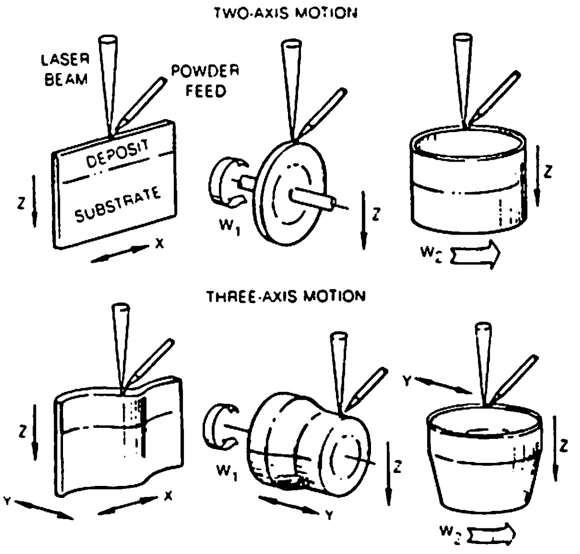

Figure 3: Layerglaze [3]

8. Other processes: Processes such as Laser vapor chemical deposition, selective electroplating driven by an electron beam or a line of small scanning electrodes, or other processes, especially processes used in the integrated circuit industry, may also be feasible for the production of micro-scale mechanical components.

Although the above stated processes are not all new, it is believed that the application of these processes to the manufacture of freeform solid three-dimensional objects by deposition of a multitude of thin layers is new with the exception of photochemical methods. There are probably many other methods of implementing the concept of Solid Freeform Fabrication that are not on this list.

Each one of these concepts has a unique set of advantages and disadvantages. Methods 1 - 3, 5 have a disadvantage in that the angle of overhang is limited (See Figure 4). Methods 6 and 7 require that the unaffected powder must be removed once the object is complete which will be an inconvenience when producing objects with internal voids.

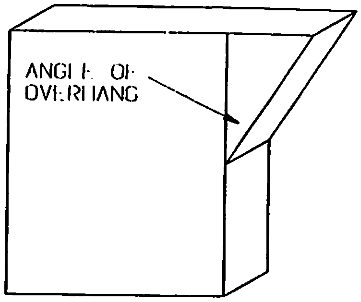

Figure 4: Angle of overhang

Secondary Processes

Several secondary processes could be used to extend the usefulness of SFF processes. The processes below were conceived to work specifically with SPS. They would produce a useful part by improving the strength of a part made by SPS or by producing a new part using the part produced by SPS as a pattern.

1. SPS + Investment casting (lost wax casting): Wax parts would be produced by SPS and then used as input to investment casting. Result: one full strength cast part of any castable material (metal, thermoset plastic, concrete, etc.).

2. SPS + Void filing: Objects produced by SPS which have open porosity could be filled with a variety of substances such as epoxy. Result: one matrix composite part.

3. SPS + Sand casting: Patterns for sand casting could be made by SPS (possibly using void filling). Result: casting pattern from which a multitude of cast parts may be made.

4. SPS using cement and aggregate: Produce a part for a mixture of metal powder and plastic binder. The resulting part will then be removed from the unsintered powder and repacked in a casting sand or investment plaster. The resulting pre-filled mold will then be heated to drive off the binder and to sinter or melt the metal powder. This process will also be applicable to ceramic powders. Result: one cast metal part or sintered metal or ceramic part.

5. SPS + Vacuum molding: Produce a form with SPS then vacuum mold composite panels to the form. The open porosity of the form will make distribution of the vacuum simple. The form would then be destructively removed. Result: one molded composite panel.

6. SPS + conventional machining: This approach would be useful to produce parts which have complex shapes but have a small number of close tolerance surfaces.

Applications

SFF processes can be thought of as three-dimensional computer output processes or as manufacturing processes. SFF processes will be most useful in manufacturing if they are considered as one additional tool in the CAD/CAM toolbox rather than as stand-alone processes. The cost of creating a computer model of the object to be produced solely as an input to these processes will offset some or all of the savings associated with these processes. Therefore, SFF processes will be most useful as part of a multi-function CAD/CAM system. The applications of SFF, and specifically SPS, and the associated secondary processes can be grouped into three categories:

1) Three-dimensional visualization: The objective in these applications is to convey a three-dimensional image to the eye of a human. The material strength needs only to be sufficient to allow handling by humans. The dimensional tolerances need to be close enough to convey the information about the shape that is normally picked up by the human eye. Examples: design visualization models, site layout models for construction, battle field layout models, output from finite element analysis, output of three-dimensional graphics, output from medical imaging, and output from electron microscopes.

2) Functional models and tools: In these applications the objects would need to have close tolerances but would not have to be high strength. Examples: casting patterns, wind tunnel models, and product mockups.

3) Functional parts: In these applications the object would need to have close tolerances and good material properties. Examples: prototype parts, replacement parts in remote locations such as space or in a war zone, parts on demand, parts that are difficult to produce by conventional processes and input to a flexible manufacturing system.

Current Experimental Work

The feasibility of method 7, Selective Powder Sintering (SPS), is currently being evaluated at the University of Texas at Austin by the authors. An experimental apparatus has been assembled and is successfully producing simple shapes. The experimental apparatus consists principally of: 1) a 100 watt NdYAG industrial laser and associated optics, 2) an X-Y beam deflection system which uses two mirrors actuated by galvanometers, and 3) a microcomputer with associated interface hardware. The powder used is black ABS plastic ground using a knife mill. The material properties and dimensional properties of the objects produced show promise.

Apparatus

The experimental apparatus used in the first round of experimental work is shown in Figure 5. The laser is placed horizontally. A set of lenses is mounted on the laser rail to focus the beam. The beam is then directed by a prism into the X-Y deflection system. The output beam travels downward and is focused on the bottom of a container that is placed approximately three feet (one meter) below the galvanometer assembly.

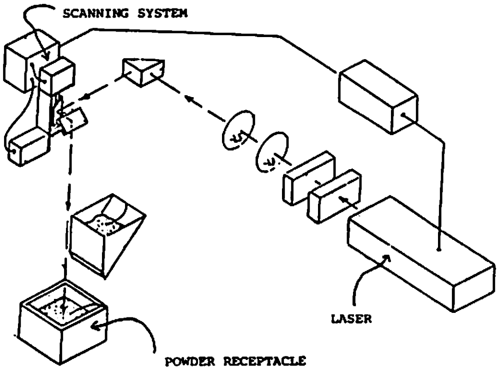

Figure 5: Experimental apparatus

A raster pattern can be produced on the bottom of the container using the X-Y deflection system. Two-dimensional patterns can be irradiated by modulating the laser in synchronization with the raster scanning in the same way that the electron beam is modulated in a cathode ray tube. (see Figure 6)

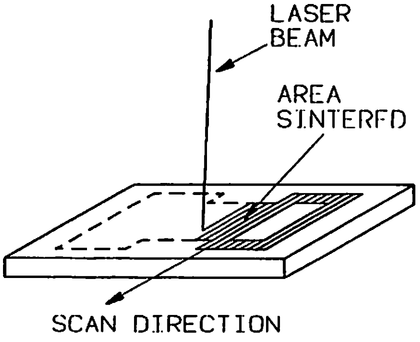

Figure 6: Raster scanning a layer of powder

Experimental Procedure

Powder is deposited into the container from above. The laser is then turned on and the powder is selectively irradiated. The powder which occupies the voxels that are to become the first layer is irradiated and the rest of the powder is not irradiated. This heats the plastic powder in those voxels sufficiently that the powder sinters. Sintering occurs when the surface tension overcomes the viscosity of the plastic and the particles flow together and bond. The overlap of the focal spot is great enough that adjacent lines which are irradiated will sinter together creating a coherent layer of sintered material. In the region that is not irradiated, the powder remains loose. More ABS powder is deposited into the container as the laser is scanning so that once the beam is finished with one complete scan and starts over, another layer of fresh powder is on top of the previously sintered layer. This new layer is sintered selectively in the two-dimensional pattern that corresponds to the second cross-section of the object to be produced. The layers are approximately .005 inches (0.125 mm) thick. Each layer is sintered deep enough to tie it to the previous layer. This process is continued until the desired object is produced. The object is surrounded by powder as shown in Figure 7.

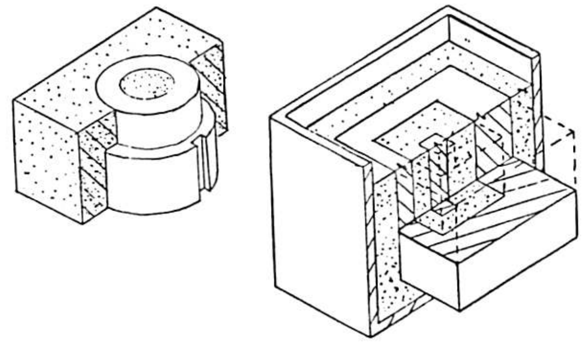

Figure 7: Objects surrounded by unaffected powder.

Typical input parameters are:

Power = 90 watts

Time per layer = 20 sec.

Lines per frame = 256

Spot size = 0.02 inch (0.5 mm)

Layer thickness = 0.005 - 0.010 inch (0.125-0.250 mm)

Raster pattern size = 3.0 x 3.0 inch (75 x75 mm)

Layers per part = 128

Time per part = 46 min.

Major Results

1) Simple three-dimensional objects were produced after only two months of lab work as shown in Figure 8.

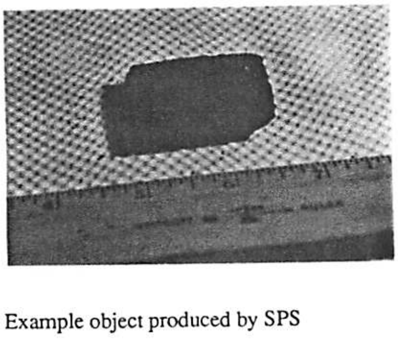

Figure 8: Example object produced by SPS

2) Large particles (-20 + 40 mesh) led to higher strengths but poor dimensional properties.

3) Small particles (-80 mesh) led to better dimensional properties but poor strengths.

4) When using the small particles, the layers curled up at the edges when high power was used. Higher power could be used with the large particles but a limit was reached when excess powder input caused a bulk heating of the built up object that would cause the object to grow into the unsintered material in an uncontrolled manner.

5) It was later observed that there was a correlation between the size and the morphology of the particles as produced by the knife mill. Small particles tended to have low aspect ratios and large particles tended to have large aspect ratios. The correlation between size and properties mentioned in observations 2 and 3 may be actually a correlation between aspect ratio and properties.

6) Objects produced generally have low density, open porosity and a matrix structure.

At the end of the first round of experiments several needs were apparent:

1) A process model is needed. There are thirteen or more important input parameters which makes an exhaustive search-type experimental procedure impractical for identifying the optimum input parameters. These input parameters are: beam spot size, beam power, lines per layer, fast axis size, slow axis size, fast axis scan frequency, powder deposition rate, effective powder size, effective powder aspect ratio, absorption coefficient of the powder, scattering coefficient of the powder, heat transfer coefficients before sintering, heat transfer coefficients after sintering. Not all of the input parameters are independently controllable. A non-dimensional process model is needed that will allow a smaller number of non-dimensional input parameters to be varied, and will predict the direction that a particular non-dimensional input parameter should be varied to correct a particular problem with the objects produced. The effects of powder composition and morphology need study.

2) The experimental apparatus needs to be upgraded so that the operational parameters can be better controlled. A method needs to be developed to feed the powder evenly and repeatedly. The beam focusing needs to be improved.

Work in Progress

A comprehensive process model has not yet been constructed but several important effects have been theorized as follows:

1) The heat conduction coefficient of the powder increases dramatically upon sintering. This is due to the elimination of contact resistance between the particles and the increase in contact area between the particles.

2) If a volume of powder is being sintered by heat conducted in from one direction, then changes in the heat conduction coefficient may lead to a situation in which the sintering front moves one particle at a time, as shown in Figure 9. Particles 1 and 2 in Figure 9 are well sintered. Particles 2 and 3 are in the process of sintering. The row of particles will act as a set of linked first order systems with the time constants of each first order system dependent on the degree of sintering. As particles 2 and 3 sinter, the time constant for the heat conduction between particles 2 and 3 will reduce and the sintering will accelerate. But the time constant for heat conduction between particles 3 and 4 will remain at the original longer value until particle 3 is heated to the extent that it starts sintering to particle 4. In this way, the sintering front will move one particle at a time as the sintering front moves into material where no sintering has yet occurred.

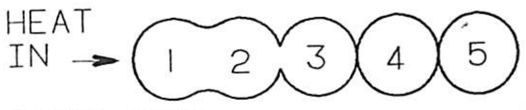

Figure 9: Sintering example.

3) The energy input distribution from a single scan of the laser beam will look like Figure 10. The temperature just after the beam passes will range from a maximum value on the surface at the center where the powder is heated more than is required to achieve full sintering to a temperature at the edges which is just high enough to cause small necks to form. In order to have sharp boundaries, the sintering front must move into unsintered material. For this to occur, enough energy must be deposited to bring the volume in which some sintering occurs to a temperature at which full sintering will occur plus some excess to ensure boundary motion. This requires enough excess energy at the center to make up for the deficit towards the edges.

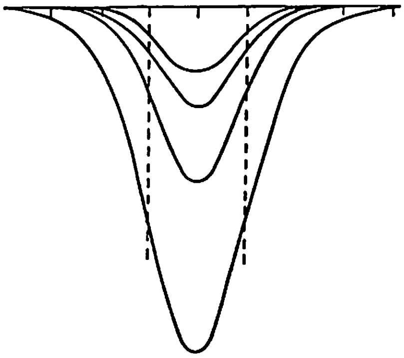

Figure 10: Energy input distribution.

4) It is desirable to have the state of each voxel independent of the state of other voxels. It is necessary to have a mechanism that will ensure adequate sintering of each voxel without overheating of the voxel regardless of the initial temperature of the voxel (the initial temperature will be affected by the state of the surrounding voxels).

5) If the sintering front grows into the previous layer and the previous layer has cooled sufficiently, then the previous layer will act as a heat sink once good thermal contact is established between the line just sintered and the previous layer. This will stop the growth of the line just sintered and help maintain dimensional control. Good thermal contact between the line just sintered and the previous layer will ensure good bond strength since both bond strength and thermal contact are dependent on bond area. This mechanism can be used as a feedback mechanism so that small variations in the beam power or the initial powder temperature do not integrate over several layers. In order to get the benefit of this mechanism, it is necessary to adjust the layer thickness so that each layer will just grow into the previous layer and to ensure that the previous layers are cool enough. This links the maximum power that may be applied by the laser to the heat transfer out of the object as it is built up.

6) When two spheres are sintered, the centers of the spheres move toward each other. If spheres are used in SPS, then the motion of the centers of the spheres will cause a three-dimensional shrinkage which will cause the part to warp. If high aspect ratio flakes are used instead of spheres, and if the flakes are oriented preferentially in the horizontal plane, then the shrinkage will be primarily in the vertical direction and the warping problem will be reduced. This is because of the greater number of degrees of freedom that the flakes may move in to accommodate bonding. Flakes can rotate, twist, and bend which would have no effect on a sphere. The motion of the centers of the spheres toward each other is the only degree of freedom that will allow bonding in spheres. Also, the orientation of the contact patches preferentially in the horizontal plane will cause what shrinkage that will occur to be primarily in the vertical direction. Depositing the particles from above so that each particle falls independently should produce the desired particle orientation. It has been shown that the sintering speed increases as the size decreases [5]. The optimum particles will have small size and high aspect ratio.

The following equipment upgrades are under way or are planned for the near future:

1) An automatic powder feeding and leveling system is under development.

2) The focal spot size will be reduced by applying existing laser scanning technology.

3) Conventional grinding technologies will be used to produce powders of the desired size and morphology.

The second round of experimental work will be conducted using the improved apparatus during the spring and summer of 1987. The objective will be to: 1) determine the optimum operating parameters, 2) confirm and refine the process model, and 3) quantitatively evaluate the capabilities of SPS.

Research Issues

Some long range research issues are:

1) How far can SPS be scaled up or down?

2) How much can SPS be speeded up? Transferring heat out of the system appears to be a limiting factor.

3) Will thermal stress problems limit the material strengths attainable?

4) What are the best tolerances attainable?

Conclusions

A concept for a new class of manufacturing processes called Solid Freeform Fabrication (SFF) has been presented. SFF will produce solid three-dimensional objects directly from a computer model of the object without part specific tooling or human intervention. Several concepts for the implementation of SFF have also been presented. One of these concepts, Selective Powder Sintering, is under experimental evaluation at The University of Texas at Austin. Another implementation of the SFF concept, Stereolithography, is being developed independently. Once developed, SFF and SPS in conjunction with CAD/CAM should significantly reduce the cost and speed up the production of low production number mechanical components. One effect of this will be a reduction in product development time. The concept of SFF presents a new interdisciplinary frontier in manufacturing research.

REFERENCES

1. Cathcart, R. D., Heydinger, M. D., Petrakis, G. O., "Feasibility Study of Robot-Controlled Wire-Welding to Build Up Primary Telescope Mirror Substrates", ME 366KFinal Report, Department of Mechanical Engineering, University of Texas at Austin, Spring, 1986.
2. Hull, C. W., U.S. Patent 4,575,330, Mar. 11, 1986.
3. E. M. Breinan, D. B. Snow, C. O. Brown, B. H. Kear, "New Developments in Laser Surface Melting Using Continuous Prealloyed Powder Feed", Rapid Solidification Processing, Vol. II, Claitors Publishing,1980.
4. Deckard, C. R., "Part Generation by Layerwise Selective Sintering", Master of Science Thesis, Department of Mechanical Engineering, University of Texas at Austin, May 1986.
5. Rosengweig, N., Markis, M., "Sintering Rheolog of Amorphous Polymers", Polym. Eng. Sci. 21, 1167 (1981).