IMPROVED ENERGY DELIVERY FOR SELECTIVE LASER SINTERING

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ABSTRACT

Selective Laser Sintering (SLS) is a leading technology in the important new area of Solid Freeform Fabrication (also called Rapid Prototyping). Selective Laser Sintering produces freeform parts directly from a CAD model by building the parts up in layers from a powder. A laser is used to selectively melt each layer of powder to form the part. The laser beam is scanned across the powder using two galvanometer scanners. The energy delivery system (laser, optics, scanner and controls) is a critical component technology of SLS. Projects with the objective of improving the energy delivery system are underway at Clemson University.

1. INTRODUCTION

Selective Laser Sintering (SLS) is a leading process in the new field of Solid Freeform Fabrication (SFF). SLS produces parts directly from a CAD model by melting or sintering thin layers of a powder together with a laser beam. SLS is a thermal process that is applicable to a wide range of materials.

At Clemson, we are working on SLS with the objective of developing process understanding that will lead to system performance improvements. We are concentrating most of the research effort on the energy delivery system (laser, optics and scanner). Our near term focusing objective is to improve the part production speed. Control of the thermal gradient within the layer being sintered (or melted) has been identified as a key process issue.

2. BACKGROUND

2.1 Statement of Need SLS and other SFF processes have the potential to become indispensable, mainstream industrial processes. At this time, SLS and other SFF processes are primarily used by large companies and service bureaus to make small production number high value parts. To extend SLS and other SFF processes to new applications and users, continuous improvement in process performance is needed. Several key performance measures are: 1) accuracy, 2) material properties, 3) part production speed, 4) surface finish, 5) part production cost, and 6) maximum part size. Improvements in several areas are needed to achieve these performance improvements. These areas include: materials, machines (hardware and controls) and software.

2.2 Current Energy Delivery System The energy delivery system hardware currently used in commercial SLS machines consists of a laser, focusing optics, and a scanning system.

The laser is a commercially available 50 watt CO_2 laser. A two lens system is used to focus the beam. The scanning system consists of two mirrors which are rotated by galvanometers to deflect the laser beam to the desired position. The galvanometers are controlled by an analog PID loop and a servo amp. The set points are generated by the scan computer in response to vector data provided by the process control computer.

The scan pattern generally consists of an outline and a parallel line fill pattern (Fig. 1). The spacing between the scan lines is generally one half to one quarter of the beam diameter; therefore, each point to be scanned is hit by the laser beam two or more times (Fig. 2). The laser beam spot size is generally around 0.4 mm. The minimum attainable laser beam spot size is governed by diffraction of the laser beam and the maximum desirable spot size is set by the need to produce parts with fine features.

2.3 Laser Material Interaction and Heat Transfer Some of the beam energy is reflected by the powder and the rest is absorbed by the powder. The depth of penetration of the laser beam into the powder bed is a function of the optical properties of the powder at the laser wave length (1). See Figure 3. The intensity of the laser beam within the powder bed as a function of depth is:

$$I(z) = (1 - R)I_0 \exp(-bz) \tag{1}$$

Where:

R = surface reflectivity

I_0 = laser light intensity at the surface

β = extinction coefficient

z = depth into the bed

The absorption of the beam by the powder creates a three dimensional heating of the powder. The heat input distribution is a decaying exponential multiplied by the spot profile (usually a gaussian). The energy input at a point is time varying due to the motion of the beam. From reference (1), the heat source function is:

$$g(x,y,z,t) = (1 - R)\beta I_0 - \exp\left[-\frac{(x - v_x t)^2 + (y - v_y t)^2}{w^2} - \beta z \right] \tag{2}$$

Where:

x,y = horizontal position of the point in question

$g(x,y,z,t)$ = heat input as a function of position and time

t = time

w = spot size

v_x = beam velocity in the x direction

v_y = beam velocity in the y direction

The resulting temperature distribution is the initial condition for a three dimensional transient heat transfer problem with variable coefficients (1). The heat transfer is described by the conduction equation:

$$\rho C \frac{\partial T}{\partial t} = \nabla(k \nabla T) + g(x,y,z,t) \tag{3}$$

Where:

ρ = density
C = specific heat
k = thermal conductivity

The density and the thermal conductivity change with degree of sintering. Radiation and convection from the surface must also be considered. This problem has been dealt with in great detail by other authors (1). The full results are not presented here but some general conclusions should be noted. If the laser beam interaction time is small with respect to the time constant for heat transfer, then the thermal gradient is primarily a function of the average temperature rise of the powder layer due to the one pass of the laser and the extinction coefficient. If the laser beam interaction time is on the same order or longer than the time constant for heat transfer, then the thermal gradient will be lower than predicted above due to heat transfer during the laser material interaction.

2.4 Significance of Thermal Gradients Laser material processing is normally characterized by larger heat fluxes and as a result, large thermal gradients. Large thermal gradients are a significant feature of the SLS process. The acceptable numerical range for the thermal gradient is bounded. If the thermal gradient is too low, then the part will not have well defined edges. If the thermal gradient is too large, then the surface temperature will be too high (a minimum average temperature must be reached to give the desired amount of sintering or melting). Several negative effects are associated with an excessively high surface temperature. These effects include: 1) thermal degradation and/or oblation of the surface, 2) balling of the surface, and 3) excessive heat loss from the surface due to radiation and convection.

2.5 Controlling the Thermal Gradient In early SLS experiments, it was observed that the thermal gradient was too high and steps were necessary to reduce the gradients into the acceptable range. The excessive thermal gradient was manifested by a balling phenomenon (at that time called the "spider web structure") and by degradation of the material (2). To relieve these problems, a combination of the approaches presented below was used.

The issue of controlling thermal gradients within the layer must be addressed as we work to increase the scan rate (area scanned per unit time). An increase in the scan rate requires an increase in the rate of laser energy input to the part. To do this, it is desirable to use more laser power and to reduce the proportion of the laser energy that is lost from the surface due to oblation, radiation and convection. A better understanding of the factors affecting the thermal gradients and methods of limiting the thermal gradients is necessary.

Several approaches can be used to reduce the thermal gradient:

1) Increase the part bed temperature. This reduces the laser beam energy that is required to accomplish the sintering (or melting) of the powder and therefore the thermal gradient. The part bed temperature is limited due to part growth or caking of the part bed (non selective sintering of the powder outside of the part).

2) Reduce the extinction coefficient. In many cases we do not have control over the optical properties of the powders. Also, this strategy is limited by the increase in reflectivity of the part bed as the extinction coefficient becomes small with respect to the particle size.

3) Increase the laser beam interaction time. This can be done by a) reducing the linear scan speed and reducing the laser power, b) increasing the laser beam spot size, or c) using more beam overlap (less spacing between the scan lines for a given laser beam spot size).

Once a material is selected and the maximum part bed temperature has been determined, then increasing the laser beam interaction time is the primary tool that can be used to reduce the thermal gradient. If increasing area scanned per unit time is an objective, then a reduction in the linear scan speed is not an attractive option. Therefore the two approaches that appear most attractive are increasing the laser beam spot size and using more beam overlap.

2.5.1 Increasing Beam Overlap Currently in SLS, it is common to use a beam overlap of 2 to 4 (the spacing between adjacent scan lines is 1/2 to 1/4 of the laser beam spot size). Each point to be sintered (or melted) is hit by the beam 2 to 4 times. Heat is conducted away from the surface into the layer between passes of the beam and this reduces the thermal gradient. Heat is also radiated and convected away form the surface during this time. For these reasons, the time between scan lines is a significant factor in determining the thermal gradient and the degree of sintering (or melting) of the layer. Figure 4 shows the temperature at a point as a function of time and the influence of time between scans and the maximum temperature. If a simple parallel line fill pattern is used, then the time between scans may not be uniform across the crossection (Fig. 5). Differences in material properties have been observed due to variation in the time between scans. For these reasons, it is desirable to take steps to bound the time between scans.

2.5.2 Increasing the Laser Beam Spot Size Current commercial SLS machines use a spot size of 0.4 mm. Increasing this spot size would increase the laser beam interaction time for a given scan speed, and the scan spacing could be increased while maintaining the same scan overlap. The disadvantage of this approach is that it increases the minimum feature size. For this reason, a dual beam size system is desirable. The small beam would be used for outlining and small features; and the large beam would be used to fill larger areas.

3. OBJECTIVE

The main objective of the SLS research at Clemson University is to further develop an understanding of the SLS process with an emphasis on the energy delivery system. Of particular interest is the effect of scanning parameters and techniques on strength, speed and system robustness. This understanding will be used to speed up the scanning process while producing parts with equal strength and accuracy.

3.1 Hypothesis Limiting the thermal gradient in the layer during the laser material interaction is a key issue in SLS. Addressing this issue will lead to an increase in the scan rate (3).

3.2 Approach An experimental approach is being used. Test bars are being fabricated and strength tested. Designed experiments and parameter trade-off studies are being conducted.

3.2.1 Equipment An SLS process research workstation has been built. This machine is similar to commercial SLS machines in its general configuration. The primary differences are: 1) this machine incorporates the unique feature of a variable beam spot size, 2) the oven has been enlarged horizontally in an effort to reduce the effect of the oven walls and the feed heaters on the part temperature distribution, and 3) the oven height has been reduced to reduce natural convection.

The variable beam spot size capability was accomplished by placing an aperture at an intermediate focal spot. The aperture can be inserted or removed from the beam path under computer control using a solenoid. The large spot is 1 mm in diameter and the small spot is 0.3 mm in diameter. The approach is simpler than using zoom optics and allows the energy density to be kept constant without adjusting the laser power. To design the variable beam spot size optics, computer modeling (ray tracing) of the beam and optics was done. Significant work was required to find a combination of standard lenses to accomplish this capability.

3.2.2 Experimental Procedure Test bars are being produced from a polymer coated metal powder and strength tested. The test specimens conform to the Metal Powder Industries Foundation (MPIF) Standard 15, (31 mm long x 13 mm wide x 6 mm thick).

Testing of the parts per MPIF Standard 15 will be conducted on an Instron Model 1321 tension/compression machine. The parts will be subjected to a three point bending test as per the specification at a stroke rate of 12 μm/sec. The data will be collected using Labtech Notebook and complied for analysis using a spreadsheet.

3.2.3 Status and Experimental Plan We have conducted screening tests to find a range of parameters that produce parts with the desired degree of sintering. The parameters varied were: beam spot size, scan speed, scan spacing, time between scan lines, and laser power. We are now conducting designed experiments to evaluate the relationships between the parameters of interest. Next we will conduct parameter trade-off experiments. We will look at the trade-off between scan speed and scan spacing and evaluate the merits of the variable beam spot size strategy. We will then map the edge of the parameter space in the areas of interest.

The robustness of the solution will then be evaluated. The most significant robustness issue is the effect of time between scan line on the part strength.

4. CONCLUSION

Key issues which define the requirements for the energy delivery system in the SLS process have been presented. These issues are driving the SLS process research at Clemson University. This work should lead to an improvement in the SLS process.

5. ACKNOWLEDGMENTS

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6. REFERENCES

1. M.M. Sun and J.J. Beaman, Solid Freeform Fabrication Symposium, 102, (1991).

2. C.R. Deckard, Selective Laser Sintering, Ph.D. Dissertation, University of Texas, 1988.

3. J.W. Barlow, Personal communication, 1988.

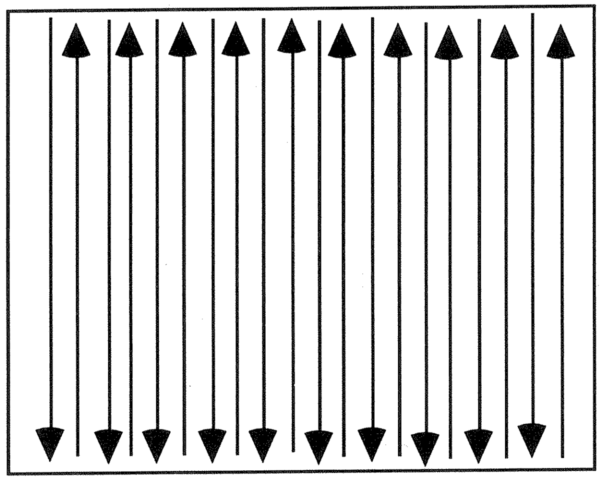

Figure 1. Scan pattern

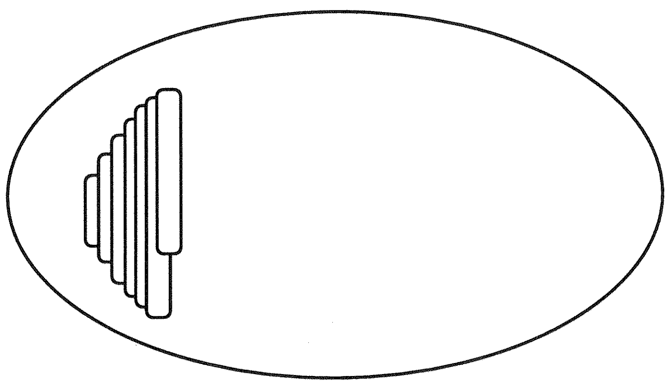

Figure 2. Partially filled outline showing beam overlap

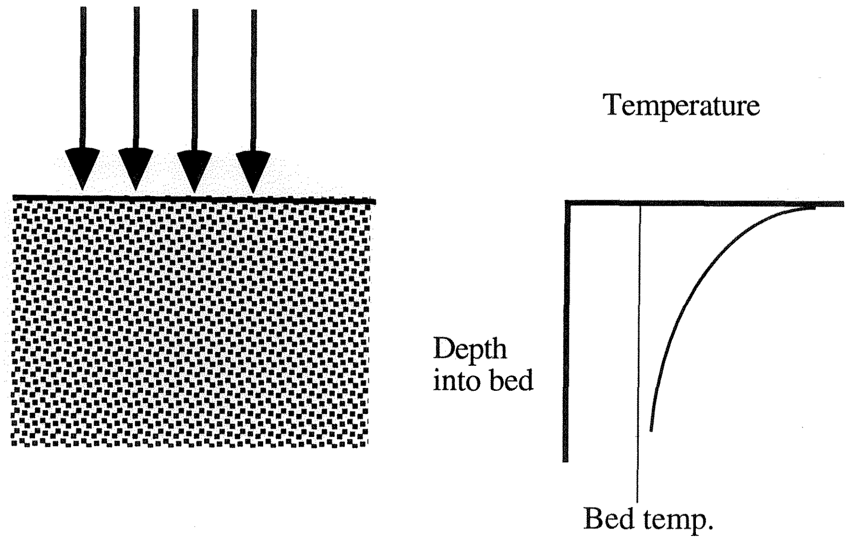

Figure 3. Temperature vs. depth

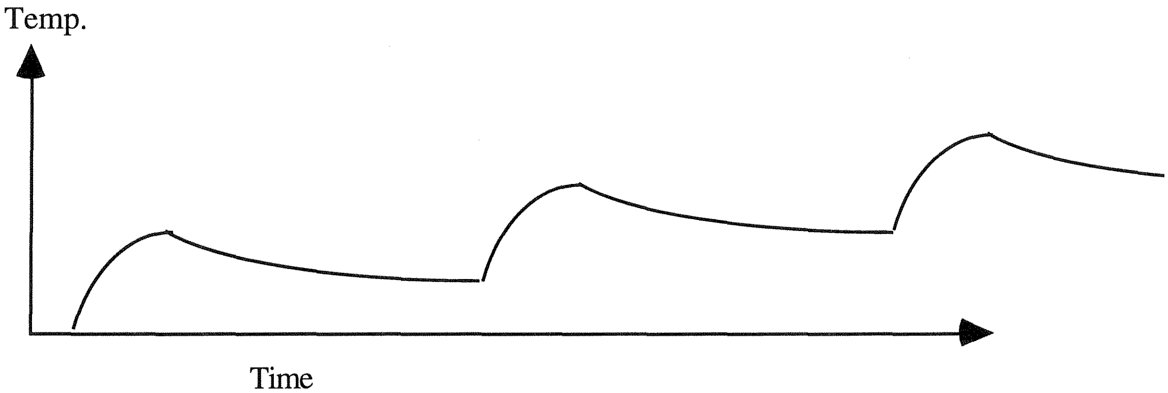

Figure 4. Time vs. temperature at a point

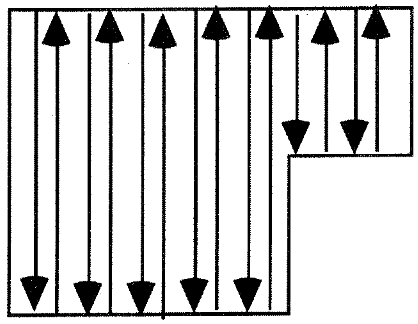

Figure 5. Variation in vector length as a function of geometry. This leads to a variation in the time between scans.