

# **Relating Operating Parameters between SLS Machines which have Different Scanner Geometries and Laser Spot Sizes**

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## **Abstract**

As the number of SLS machines in operation increases, the opportunities to share operating parameters with other SLS operators also increases. However, if the machines are not identical down to the spot size of the laser beam, the quality of parts made on each machine can be different. The most likely differences between two SLS machines are the laser spot size and the scanning radius of the optics. The total energy flux to the powder surface is a function of the spot size and the scan speed. The algorithms defined to correct for machine differences are verified both experimentally and numerically using a one-dimensional empirical SLS model.

## **Introduction**

The art of Selective Laser Sintering (SLS) has developed significantly over the past several years, but there are still gray areas that are not fully understood. Computer control is one such gray area. Ideally, the SLS machine should automatically set parameters and produce a sintered part once the material system has been specified. However, operation of an SLS machine will remain as an interactive process between the operator and the machine until an optimal set of operating parameters is found. These operating parameters are both powder specific and sometimes machine specific. This paper deals with the machine specific aspects of the operating parameters.

Understanding the machine specific parameters, which include the laser scanning radius and the laser spot size, is important in the development of algorithms that will correct for differences between SLS machines. Machine differences can be compensated for by modifying the controllable operating parameters like beam speed and laser power. As new materials are developed for use in the SLS process, the importance of generalizing the operating parameters will become evident. The consumer should not have to spend his time to find a good operating range for new material when the material supplier could supply a set of SLS operating parameters along with the specifications of the SLS machine that was used to process the material.

There are numerous combinations of the SLS operating parameters that can be used to make good quality sintered parts. This paper does not provide a guide line for the operating parameters that should be used in the SLS machine, rather this paper is a tool that allows one to modify a set of operating parameters to work on any SLS machine. The operating parameters derived by the following methods have been used to make test parts in an SLS machine and have been simulated numerically using a multilayer sintering model.

## **Description of Parameters**

The amount of energy that is applied to the powder surface during SLS is a function of several operating parameters which include laser spot size, scan radius, laser power, scan spacing and the laser scanner parameters (*SS* and *SP*). The size of the laser spot and the scan radius are both machine specific and may differ from one SLS machine to another.

The flow diagram in Figure 1 shows how the energy to the surface is a function of the operating parameters. The energy input at the surface is a function of the flux of the pulse, the duration of the pulse, and the delay between successive pulses. These three parameters are calculated as a function of the independent operating parameters. The calculation of the energy input is based on the assumption that the laser output has a Gaussian intensity distribution. This assumption is valid for the CO<sub>2</sub> laser that is most commonly used in the SLS process.

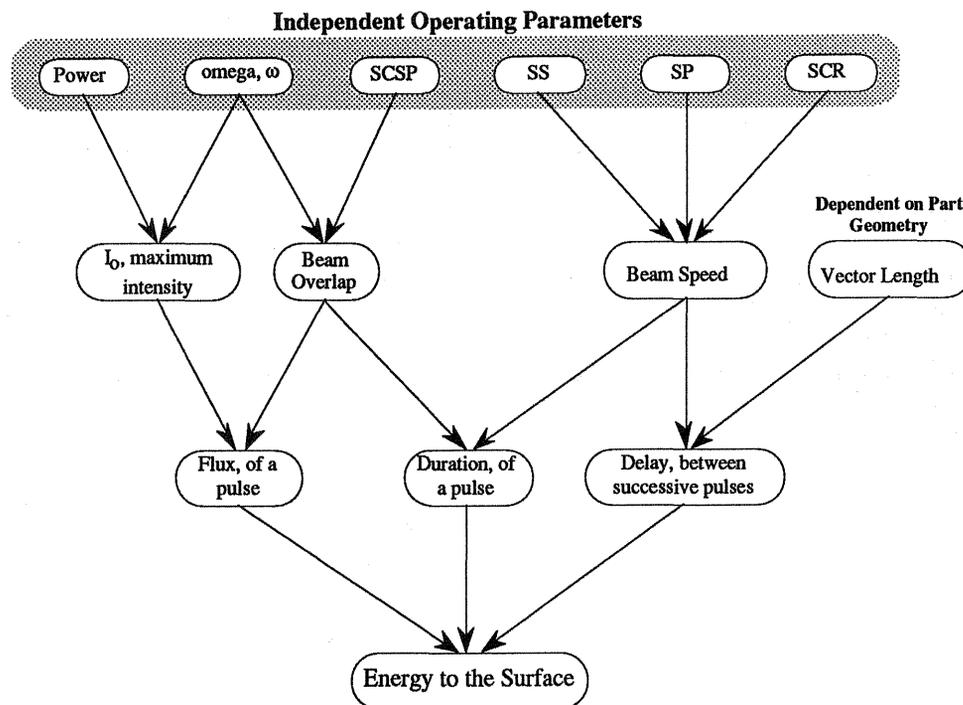


Figure 1 A flow diagram showing how the energy input at the surface is a function of the operating parameters.

#### Independent Operating Parameters

The **laser spot size** can be represented by a characteristic radius,  $\omega$ , that can be measured using a beam profilometer. The beam profilometer measures the intensity profile across the laser spot at the surface of the powder bed using a knife edge method [1]. The maximum intensity is in the beam center and decreases radially as shown in equation (1).

$$I = I_0 \exp\left(\frac{-2 r^2}{\omega^2}\right) \quad (1)$$

The **scan radius**, SCR, is the distance from the fast axis scanning mirror to the sintering plane. The maximum scan width is determined by the scan radius because the galvo mirrors only have a range of 40° over the surface of the powder bed. The scanning speed is a function of the scan radius and the laser operating parameters as shown in equation (2).

$$\text{beam speed} = 1.04378 \left( \frac{SS * SCR}{SP} \right) \quad (2)$$

The **laser power** is often the preferred parameter to adjust by the operator during processing because it is easy to adjust and results are intuitive. When the power is increased, the energy at the surface is increased. The power tuning knob can be calibrated prior to sintering which allows the operator to make small adjustments in the laser power.

The **laser scanner parameters**, *SS* (step size) and *SP* (step period), specify the speed at which the galvo mirrors turn and in conjunction with the scan radius define the beam speed. However, there is a range for *SS* and *SP* outside of which the scanners may reach a mechanical limitation. If the step size is too large or if the step period is too short, the actual beam speed will deviate from the beam speed calculated by equation (2).

The **scan spacing**, *SCSP*, is the distance between adjacent scan vectors. The scan spacing can be adjusted to change the amount of beam overlap during a scan prior to sintering when the layer is divided into a series of parallel scan vectors. Beam overlap occurs when the radius of the laser spot is greater than the spacing between scan vectors.

#### *Definition of Dependent Variables*

The **flux of a pulse** is a function of the maximum intensity of the laser output and the position of the beam relative to a reference point. When the radius of the laser spot is greater than the spacing between scan vectors, *SCSP*, the laser adds energy to points along adjacent scan lines causing beam overlap. The flux along an adjacent vector can be calculated by integrating the laser intensity along that scan vector, equation (3). The maximum intensity of the laser is a function of the characteristic radius and the power setting, equation (4).

$$\bar{q} = \frac{1}{S_x} \int_0^{S_x} I_o \exp\left(\frac{-2r^2}{\omega^2}\right) dx = \frac{I_o \sqrt{\pi} \omega \operatorname{erf}\left(\frac{\sqrt{2}S_x}{\omega}\right)}{S_x 2\sqrt{2} \exp\left(\frac{2(y-y_o)^2}{\omega^2}\right)} \quad (3)$$

$$I_o = 0.239 * \frac{P}{\pi\omega^2} = \left[ \frac{\text{cal}}{\text{cm}^2\text{-sec}} \right] \quad (4)$$

The nomenclature used to calculate the average flux is illustrated in Figure 2. In the figure, the laser spot overlaps a scan vector on each side of the current vector. During scanning, beam overlap preheats the powder along adjacent scan lines which increases the amount of heat that is absorbed by the powder bed.

The **duration of the pulse**, *dp*, refers to the time necessary for the beam to pass over a reference point on the scan vector and is therefore a function of beam speed and the position of the reference point relative to the beam center. The duration is equal to the length of the vector under the beam divided by the beam speed as shown in equation (5).

$$dp = 2 \frac{S_x}{bs} \quad (5)$$

The **delay between pulses** is defined as the time necessary to scan one complete scan vector. The delay includes the scanner settling time between vector scans in addition to the time required to scan the entire scan vector. As the vector length increases, the time required to scan the vector increases. The delay is therefore a function of the part geometry and the laser operating parameters, (*SP*, *SD*, and *LF*) as shown in equation (6).

$$\text{delay between successive pulses} = \left[ \frac{\text{vector length}}{\text{beam speed}} + (SD * SP * 10\mu\text{s} + LF) * 10^{-6} \frac{\text{s}}{\mu\text{s}} \right] \quad (6)$$

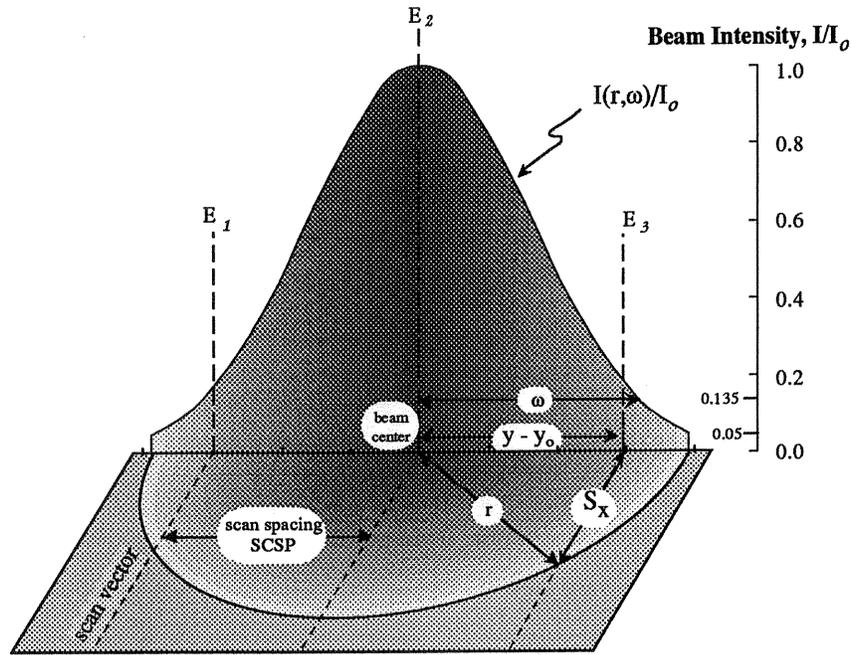


Figure 2 Nomenclature used in the calculation of flux to the surface.

## Results and Discussion

The primary goal of this paper is to define a method to generalize the operating parameters used to produce a part by the Selective Laser Sintering method. This will enable the transfer of operating parameters known to work on one SLS machine to any SLS machine that may have different machine specific parameters. The ability to transfer parameters will reduce the startup time that often accompanies new materials, if the powder supplier provides a set of well documented operating parameters with the powder. Also, these equations can be used in the development of a real-time control algorithm that would maintain a constant energy input for scan vectors of various lengths by controlling the laser power and beam speed.

The generalization of the SLS operating parameters, to allow the transfer of parameters to other SLS machines, would prove useful to anyone unfamiliar with all the intricacies of selective laser sintering. Operating parameters that were known to produce good quality SLS parts with a specific powder could be made available along with some machine specific information such as the laser spot size and the scan radius. These parameters could then be translated, using the following method, to account for any variations in the laser spot size or scan radius. The new parameters should produce an SLS part which has density similar to the original part. The linear conversion of parameters does not account for variations in the scan vector length. To adjust for variations in vector length within a single layer one would need to control the laser power and the beam speed dynamically.

### *Development of Operating Parameter Transformations*

The new operating parameters are calculated in four steps. To simplify the derivation, machine #1 refers to the SLS machine from which the operating parameters are taken and machine #2 refers to the recipient of the new operating parameters. In the following equations, a subscript 1 or 2 refers to machine #1 or machine #2, respectively.

First, the scanning speed,  $bs_2$ , is chosen. The scan speed can either remain constant or it can be changed to take advantage of a change in the scan radius.

The second step is the calculation of the laser power. The energy to the surface is a product of the average flux and the duration of the pulse as shown in equation (7). Therefore, by substituting equations (3) and (5) in equation (7), one can solve for the laser power as a function of the beam speed,  $bs_2$ , as shown in equation (8).

$$\text{energy to the surface} = (\bar{q} * dp)_1 = (\bar{q} * dp)_2 \quad (7)$$

$$P_2 = \left(\frac{\omega_2}{\omega_1}\right) \left(\frac{bs_2}{bs_1}\right) P_1 \quad (8)$$

Next, the new scan spacing is calculated. A ratio of the characteristic radii is used in this step to maintain the same amount of beam overlap. The scan spacing is reduced if the size of the laser spot is reduced as shown in equation (9). Beam overlap improves sintering because it preheats the powder during a scan.

$$SCSP_2 = \left(\frac{\omega_2}{\omega_1}\right) SCSP_1 \quad (9)$$

Finally, new values of  $SS$  and  $SP$  are calculated to maintain the beam speed chosen in the first step. Because there are two unknowns,  $SP_2$  and  $SS_2$ , in equation (2), an initial value of  $SP$  is chosen and  $SS$  is calculated using equation (10).  $SP$  represents the pause after each position change of the fast axis scanning mirror. In most cases, the default value of  $SP$  is used to calculate  $SS$ . However, if the calculated value of  $SS$  exceeds approximately 90 LSB's a new value of  $SP$  should be chosen. The limit on the value of  $SS$  is a mechanical limit that has been estimated from empirical data.

$$SS_2 = \left(\frac{bs_2}{bs_1}\right) \left(\frac{SCR_1}{SCR_2}\right) \left(\frac{SP_2}{SP_1}\right) SS_2 \quad (10)$$

**Table 1** Comparison of operating parameters. Shaded areas indicated parameters calculated by the equation outlined in this paper.

| location:<br>machine:          | UT at Austin<br>Bambi  | DTM<br>Tool #4          |
|--------------------------------|------------------------|-------------------------|
| <b>machine specific:</b>       |                        |                         |
| SCR, cm (inches)               | 30.5 (12)              | 66.0 (26)               |
| $\omega$ , cm (inches)         | 0.0622 (0.0245)        | 0.0279 (0.0110)         |
| <b>independent parameters:</b> |                        |                         |
| <u>case 1:</u>                 |                        |                         |
| SCSP, cm (inches)              | 0.033 (0.013)          | <b>0.0148 (0.00583)</b> |
| Power, W                       | 16                     | 7.2                     |
| SS, LSB's                      | 26                     | 21.6                    |
| SP, 10 $\mu$ s                 | 15                     | 27                      |
| bs, inches/sec                 | 21.7                   | 21.7                    |
| <u>case 2:</u>                 |                        |                         |
| SCSP                           | <b>0.0284 (0.0112)</b> | 0.013 (0.0050)          |
| Power                          | 16                     | 16                      |
| SS                             | 26                     | 48                      |

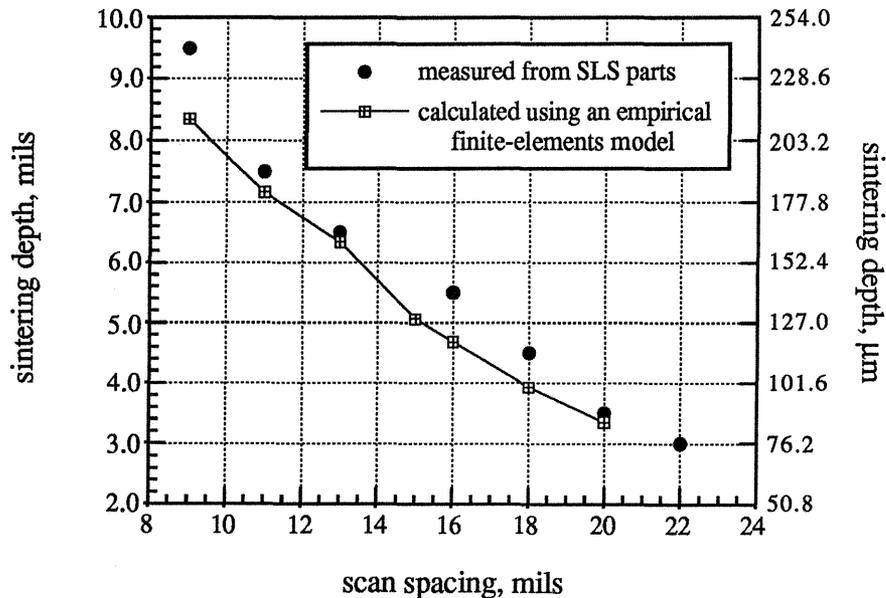
|                       |      |      |
|-----------------------|------|------|
| SP                    | 15   | 27   |
| bs                    | 21.7 | 48.2 |
| vector length, inches | 1.0  | 2.0  |

Table 1 list typical operating parameters for both the University's SLS machine and DTM's Tool #4. The machine specific parameters, characteristic radius of the laser beam and the scan radius, are also listed for each machine. The shaded areas represent operating parameters calculated using the equations (8) through (10). The differences in the beam size and the scan radius between the two SLS machines are large compared to the differences that would be present between similar SLS machines manufactured by DTM.

*Evaluation of Parameter Transformations*

The evaluation of the parameter transformation equations can be done using an empirical sintering model which differs from previous theoretical sintering models [2,3] in the method used to calculate void fraction. The empirical sintering model is based on empirical sintering rates measured using an isothermal oven sintering technique [4]. The sintering data used in this example is for polycarbonate, which is an amorphous polymer. The model calculates the temperature and void fraction profiles within powder bed. The thermal properties of the polymer such as the thermal conductivity and the heat capacity are temperature dependent and void fraction dependent. Also, the flux input used in the empirical sintering model,  $Q(x=0,t)$ , includes a pulsed energy input related to beam overlap.

Figure 3 compares sintering depths measured from parts sintered in UT's SLS machine with sintering depths calculated numerically using a finite elements model. The sintering depths were measured optically with a microscope by viewing a thin cross-section removed from an SLS part. The sintered layer appears transparent in areas that are fully sintered and appears opaque in the areas where the powder is not sintered completely.



**Figure 3** Sintering depths of polycarbonate parts sintered in UT's SLS machine compared to depths calculated using an empirical finite elements model. (Independent parameters: Power = 16 Watts,  $\omega = 0.0245$  mils, SS = 26, SP = 15, SCR = 12 inches)

**Table 2** Sintering depths calculated for the operating parameters listed in Table 1.

| location:<br>machine: | UT at Austin<br>Bambi |                    | DTM<br>Tool #4       |                    |
|-----------------------|-----------------------|--------------------|----------------------|--------------------|
|                       | calculated<br>(mils)  | measured<br>(mils) | calculated<br>(mils) | measured<br>(mils) |
| <b>case 1:</b>        | 6.52                  | 6.5                | 6.46                 | ??                 |
| <b>case 2:</b>        | 7.14                  | 7.5                | 7.10                 | ??                 |

The sintering depths that result from the parameters specified in Table 1, are calculated using the sintering model and listed in Table 2. The measured values for the sintering depths are included when available. The calculated sintering depths show excellent agreement between layers sintered on the two SLS machines. The measured sintering depths support the SLS model results. We can see that the sintering depths are slightly smaller in the parts made on the DTM SLS machine. The energy input is identical during the processing on the two SLS machines. However, the size of the laser spot differs which leads to a difference in the amounts of heat lost from the part surface during processing. For example, as the spot size decreases the following observations can be made:

- the intensity at the center of the beam increases, equation (4),
- the surface temperature increases as a result of the energy being more focused,
- less energy is absorbed into the powder because the radiant heat losses increase and,
- the number of scan vectors is increased to ensure beam overlap.

#### *Real Time Control of the Operating Parameters*

The implementation of a real time controller to control the laser power and beam speed may become necessary to provide a uniform energy density to sintered layers which contain both long and short scan vectors. With the current vector scanning technique, the laser power and the beam speed are specified before the first layer is scanned, and they remain constant throughout the SLS process. Therefore, a series of short scan vectors would receive more energy than a series of longer scan vectors because the delay between successive pulses is much smaller.

Feed back control of the laser power would be ideal for such an application if the temperature at the laser spot could be monitored accurately. The laser power could be adjusted dynamically to maintain a constant temperature during a scan which would lead to a uniform sintering depth in the layer. However, a temperature monitoring system with the accuracy necessary is not readily available. Therefore, a feed forward controller should be investigated to maintain a constant energy density across the powder surface.

Feed forward control anticipates the energy density using the current parameters and corrects for fluctuations in the energy to the surface by controlling the beam speed and the laser intensity. Controlling the beam speed during the scan of a layer would allow for adjustments to be made for scan vectors of varying length. However, adjustment of the beam speed alone would not maintain a constant energy input. The laser power would need to be adjusted simultaneously. For example, short scan vectors would be scanned with a slower beam speed and lower laser power than long scan vectors. Implementation of a real time controller using equations (8) through (10), is relatively easy if the laser power can be controlled during the scanning process.

### *Adjustment of Operating Parameters*

Another application for equations described above is the adjustment of beam speed and laser power. Operating parameters would not necessarily have to be transferred between SLS machines to take advantage of the parameter transformation equations. Equations (8) and (10) can be used to calculate power settings for various beam speeds that would maintain a constant energy density. For example, if a set of operating parameters has produced good quality SLS parts, but the beam speed was too slow. A faster scanning speed could be chosen to reduce the total time required to scan a part, and equation (8) could be used to calculate a new laser power setting. Since the laser spot size remains constant, the scan spacing would remain constant and the power setting is simply a ratio of the beam speeds.

### **Conclusion**

Equations can be derived to describe the effects of the independent operating parameters on the energy input to the powder surface. The energy can be approximated and modified as a function of laser power, scan speed and scan spacing.

These equations can be used in at least three applications. First, operating parameters used on one SLS machine can be transferred to other SLS machine that may have a different laser spot size and scan radius. Second, a feed forward control algorithm based on these equations could dynamically control laser power and beam speeds to maintain a constant energy input during the laser scan of an SLS layer. And third, the ratio of beam speed to laser power, in equation (8), can be used to calculate power settings for various beam speeds that would maintain a constant energy density.

Verification of the transformation equations has been made both experimentally and numerically using an empirical sintering model. The sintering depths calculated for parts made from the operating parameters that resulted for the parameter transformations were very similar to the sintering depths of the original parts, Table 1.

### **References**

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### **Notation**

$\omega$  = characteristic radius of the laser beam, cm

bs = beam speed of the laser scan, in/s

$I_0$  = the maximum intensity of the laser at the beam's center, cal/cm<sup>2</sup>-s

LF = Laser Off, scanner operating parameter,  $\mu$ s

LSB = Least Significant Bits, 1 step size = 1/65536 of the full field dimension

$P$  = laser power, Watts

$p$  = emissivity of solid surface

$\bar{q}$  = average flux at a reference point along a scan line, cal/cm<sup>2</sup>-s

$Q(x=0,t)$  = laser heat source, cal/cm<sup>2</sup>-s

SCR = scan radius, inches

SCSP = scan spacing, inches

$SD$  = Scan Delay, scanner operating parameter,  $SP \cdot 10\mu\text{s}$

$SP$  = Step Size, scanner operating parameter, 10  $\mu\text{s}$

$SS$  = Step Size, scanner operating parameter, LSB

$S_x$  = the distance along the scan line from the axis of symmetry to the beam circumference

$x$  = direction of the fast axis, parallel to the scan vector

$y$  = direction of the slow axis, perpendicular to the scan vector

$y-y_0$  = the distance perpendicular to the scan vector from the beam center to the scan line