Selective Laser Sintering Part Strength as a Function of Andrew Number, Scan Rate and Spot Size

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Selective Laser Sintering has been modeled analytically and numerically, and studied experimentally. Further investigation is necessary to couple the results of modeling with experimental data. At Clemson University, numerical modeling of heat transfer phenomena is used to predict temperatures within the powder layer as a function of process parameters. Efforts are focused on delivering process speed up through improved process understanding. Initial modeling results and current understanding of the effects of process parameters on the strength properties of freeform parts produced by the SLS process are presented.

Objective

The objective of this work is to improve the understanding of the Selective Laser Sintering process in order to further improve the process by predicting "good" combinations of process parameters. Current work is focused on process understanding of heat transfer within the powder layer with process speedup as the most significant performance improvement priority.

Issues

One logical approach to process speed up is to increase the laser power and laser beam velocity proportionally. A practical limit to this approach has been found by SLS workstation operators. In fact, the maximum default laser power setting for processing of polycarbonate powder is 16-20 watts even though the commercial SLS workstations are capable of delivering about 2-3 times that power to the image plane. The energy delivery is limited due to an increase in the thermal gradient within the layer as the laser power is increased. The result is a greater peak temperature at the surface with a less significant average temperature rise within the layer. As the peak temperature increases, the heat lost by radiation increases. As velocity and power are increased the degradation temperature of the powder will be exceeded leading to a reduction in mechanical properties and a loss of energy.

Minimizing thermal gradients within the powder layer is a major process issue in SLS. Deckard [1] has proposed SLS process speed up through improved modeling and control of thermal gradients. Many research efforts, such as investigation into active energy delivery control [2], will benefit from development of a closed form model predicting physical properties of freeform parts as a function of the process parameters.

Previous Modeling

Selective Laser Sintering has been modeled analytically and numerically, and studied experimentally. Analytical modeling does not lead to a closed form solution if radiation or degradation is included. Numerical modeling and experimental studies lead to an understanding of the effects of input parameters on temperature within a layer and part strength among other physical properties. However, it is necessary to relate the results of such modeling to process understanding to produce an equation, or set of equations, for predicting part strength as a function of all the key input parameters taking into account all of the significant phenomena.

Nelson [3] has developed a relative measure of the energy density delivered to the image plane. The Andrew number, A_N, is the relative energy density defined as a function of three independent process parameters,

$$A_N \equiv \frac{P}{V \cdot HS} \tag{1}$$

where P is the laser power in [W], V is the laser beam velocity in [m/s], HS is the hatch spacing in [m] and A_N is measured in [J/m^2]. It has been shown that the energy density is useful for relating physical properties of parts built by SLS to the three independent process parameters [4]. In its simplest form, the energy density can be used to predict physical properties such as flexural strength, σ, by including an empirical constant, k_1,

$$\sigma = k_1 A_N \tag{2}$$

It is apparent that this model has some limitations. First, equation (2) predicts an extremely high flexural strength for parts produced at a very high laser power or a very low laser beam velocity. Clearly, this is not accurate. From this argument, one can see that this equation is only valid over a small range of energy density and that this equation is most useful for looking at the tradeoffs between the three independent process parameters that make up the Andrew number. Second, equation (2) does not directly account for re-radiation of the laser beam energy from the powder surface and energy lost during the time between successive scans. Third, equation (2) does not directly account for the effects of thermal degradation of the powder.

Designed experiments were conducted at Clemson University using polymer coated steel powder. Miller [5] developed a measure of build speed for the SLS process. The scan rate, SR, is defined as the area scanned by the laser beam per unit time,

$$SR \equiv V \cdot HS \tag{3}$$

where V is the laser beam velocity in [m/s], HS is the hatch spacing in [m] and SR is measured in [m^2/s]. By combining scan rate and an empirical constant, k_2, with equation (2), Miller determined the flexural strength of composite parts could be accurately predicted using equation (4),

$$\sigma = k_1 A_N - k_2 SR \tag{4}$$

Equation (4) demonstrates that a larger proportional increase in power is necessary to maintain a desired strength as scan rate is increased. This model is also only valid over a small range of energy density.

To improve understanding of the strength and physical properties of freeform parts produced by the SLS process, a model which accounts for losses due to radiation and thermal degradation in addition to the energy density is necessary.

Approach

<u>General Overview</u>: A finite difference heat transfer model is used to generate data relating maximum temperature at the surface and interior of the powder layer to input parameters. Data from the finite difference model and experimental data generated in the previous phase of the project are fit with equations of a form suggested by process understanding and research. Finally, experimental studies to verify the equation are conducted.

<u>Finite Difference Modeling</u>: A four element, one-dimensional finite difference heat transfer model with material properties which are assumed invariant with changes in temperature is used. Heat generated by previously scanned layers is ignored. The assumptions of one dimensional heat transfer and constant material properties has been shown to yield reasonable results [3,6]. The finite difference model is used to predict temperature profiles at the surface and three depths within the powder layer for a given set of material properties and process parameters. The general validity of the finite difference model was confirmed by comparing results from the one dimensional conduction model presented by Mendez [6]. For this study, laser power, laser beam velocity, scan spacing, scan line length and laser beam spot size are the five independent process parameters of interest.

<u>Determining the Equation</u>: The maximum temperature reached at each node for a combination of process parameters is recorded. A candidate equation with unknown coefficients is proposed based on process understanding. An unconstrained nonlinear optimization routine is implemented to fit the proposed equation to the simulation data determining the unknown coefficients.

Modeling Results

For the purpose of demonstration a base case is chosen using polycarbonate powder and typical process parameters listed in Table 1.

Case	Radius, R [m]	Power, P [W]	Velocity, V [m/s]	Hatch Spacing, HS [m]	Length, L [m]	Energy Density, A_N [J/m^2]
1	1.53E-4	18	1.64	5.10E-5	2.54E-2	2.15E+5
2	5.08E-4	36	1.64	1.02E-4	2.54E-2	2.15E+5

Table 1. Base case process parameters

Figure 1 shows the temperature profile for the four nodes in the finite difference model using the small laser beam spot size and the process parameters listed as case 1. In this figure the temperature at the surface is represented by the temperature at node 1, T1, and the temperature within the layer is represented by the interior node temperatures in order of increasing depth, T2, T3 and T4. Figure 2 shows the temperature profile for the same four nodes using the large laser beam spot size and the process parameters listed as case 2. It should be noted that case 2 using the large spot size has twice the scan rate, twice the number of exposures to laser beam irradiation, the same energy density and a small reduction in the peak temperature as compared to case 1 using the small spot size.

Figures 3 and 4 show the maximum temperature attained at each node while varying laser power for case 1 and 2 respectively. The figures show a linear increase in both the maximum temperature at each node and the thermal gradient with an increase in power. An overall reduction in the thermal gradient is shown for the case using the large spot size.

Figures 5 and 6 show the maximum temperature attained at each node while varying laser beam velocity for case 1 and 2 respectively. The figures show a nonlinear decrease in maximum temperature at each node as well as a decrease in the thermal gradient within the layer as laser beam velocity is increased. An overall reduction in the thermal gradient is shown for the case using the large spot size.

For the purpose of modeling, interior node 3 is used to represent temperature within the layer. Figures 7 and 8 show the maximum temperature attained at node 3 as a function of velocity for four different energy density values. In order to maintain a constant energy level, power and velocity are varied proportionally and hatch spacing is constant. The plots show that the maximum temperature attained at node 3 is constant over the range of velocity at each energy density. Therefore, equation (2) is adequate for predicting temperatures in this region. The dashed lines are the results from fitting equation (2) to the data represented in figures 7 and 8. This result is contrary to expectations. Studies have shown a great dependence of physical properties in SLS parts on the velocity, scan line length and time delay between scans [5,7]. Figures 7 and 8 seem to indicate little dependence of temperature on radiation. This leads one to believe that thermal gradients and thermal degradation have a greater influence on the physical properties of freeform parts than energy loss due to radiation.

Conclusions

Current modeling of strength properties of freeform parts built by the SLS process was presented. Further investigation into coupling experimental results with numerical modeling have been initiated. A numerical model for predicting temperature profiles within a powder layer was implemented successfully. Initial results show process parameter effects on maximum temperature. It can be concluded from the results presented that thermal gradients within the layer can be reduced and scan rate increased using the large laser beam spot size.

Contradictions between model results and process experience indicate a need for expanding the numerical model to include temperature dependence of the material properties and losses due to thermal degradation. More work is necessary to define an explicit equation which yields insight into the effects of process parameters on the development of thermal gradients and mechanical properties of SLS freeform parts.

References

1. Deckard, C., Miller, D., *Energy Delivery for Selective Laser Sintering: Issues and Directions*, Solid Freeform Fabrication Symposium, Austin, Texas, 1995

2. Benda, J., *Temperature Controlled Selective Laser Sintering*, Solid Freeform Fabrication Symposium, Austin, Texas, 1994

3. Nelson, J. C., *Selective Laser Sintering: A Definition of the Process and an Empirical Sintering Model*, Ph.D. Dissertation, University of Texas at Austin, Austin, Texas, 1993

4. Vail, N. K., *Silicon Carbide Preforms for Metal Infiltration by Selective Laser Sintering of Polymer Encapsulated Powder*, Solid Freeform Fabrication Symposium, Austin, Texas, 1993

5. Miller, D., *Design and Evaluation of a Selective Laser Sintering Process for Enhanced Speed through Variable Beam Spot Size*, Clemson University, Clemson, SC, 1995

6. Mendez, P., *Modeling of selected SFF Process Limits*, Solid Freeform Fabrication Symposium, Austin, Texas, 1994

7. Terala, K., *Feed Forward Geometric Compensation for Selective Laser Sintering*, M.S. Thesis, Clemson University, Clemson, SC, 1996

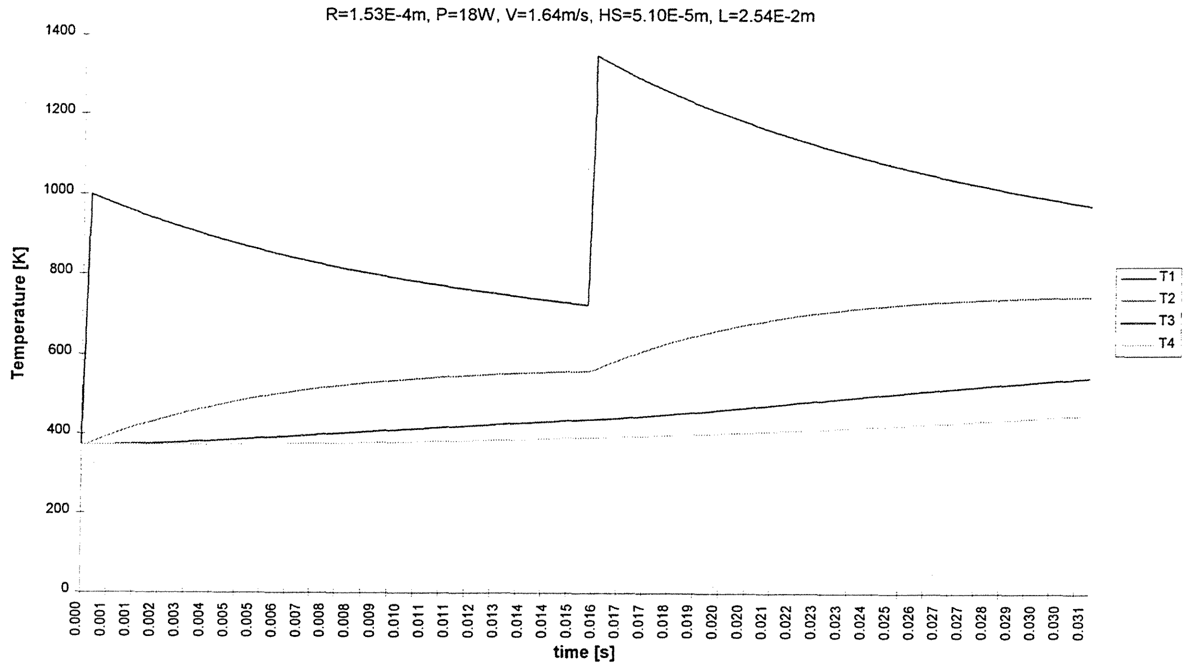

Figure 1. Temperature profile within a single layer for case 1 using the small spot size

Figure 2. Temperature profile within a single layer for case 2 using the large spot size

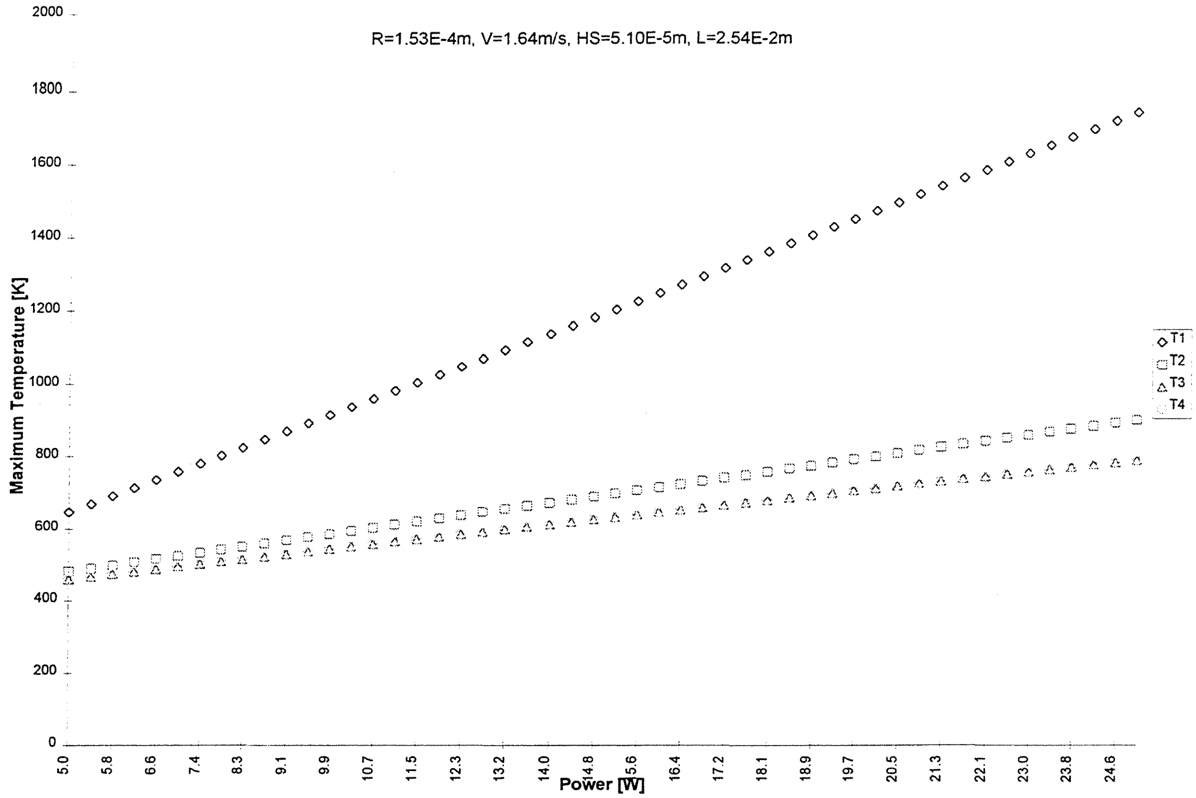

Figure 3. Plot of maximum temperature attained within a layer varying power using the small spot size

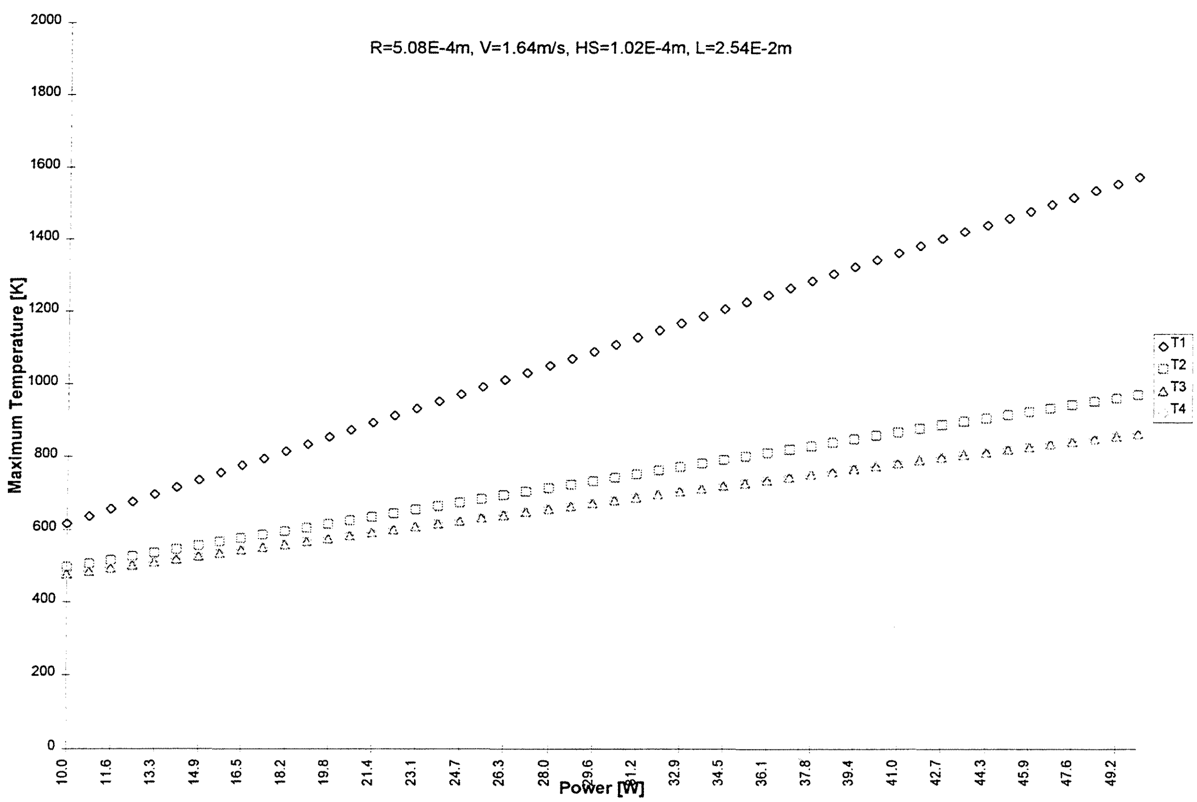

Figure 4. Plot of maximum temperature attained within a layer varying power using the large spot size

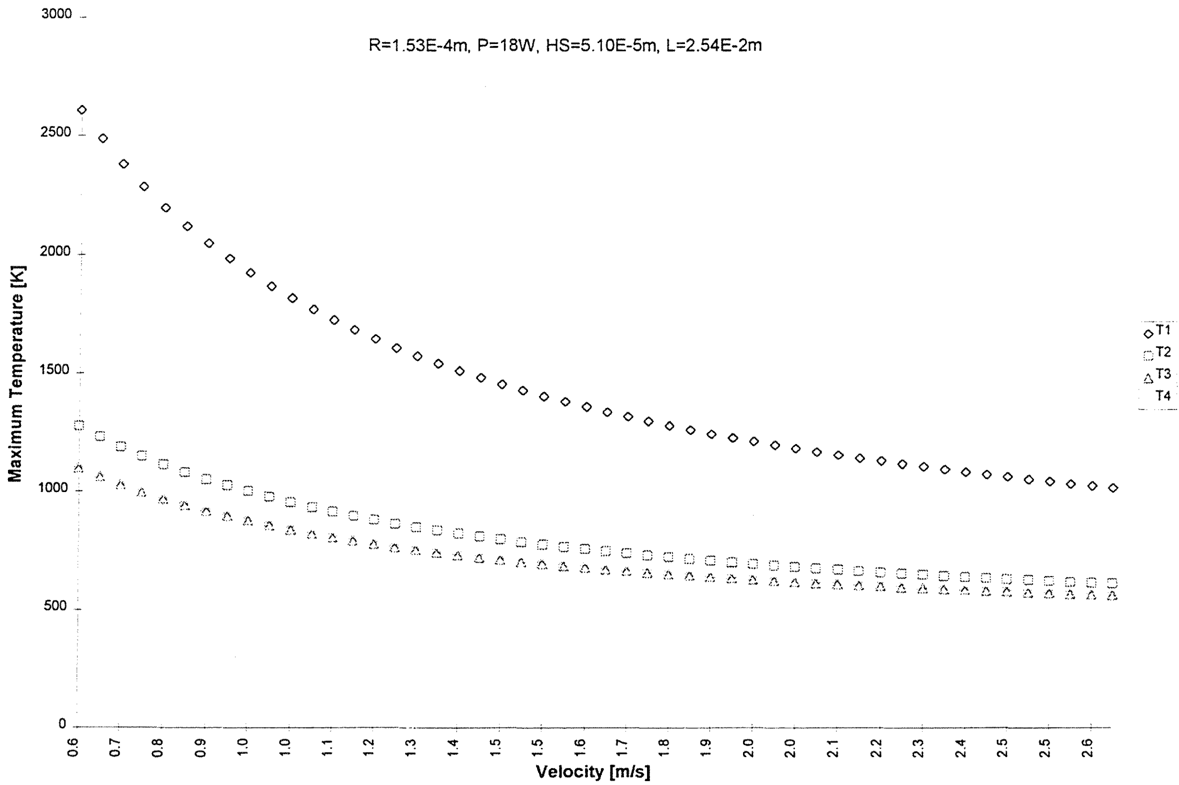

Figure 5. Plot of maximum temperature attained within a layer varying velocity using the large spot size

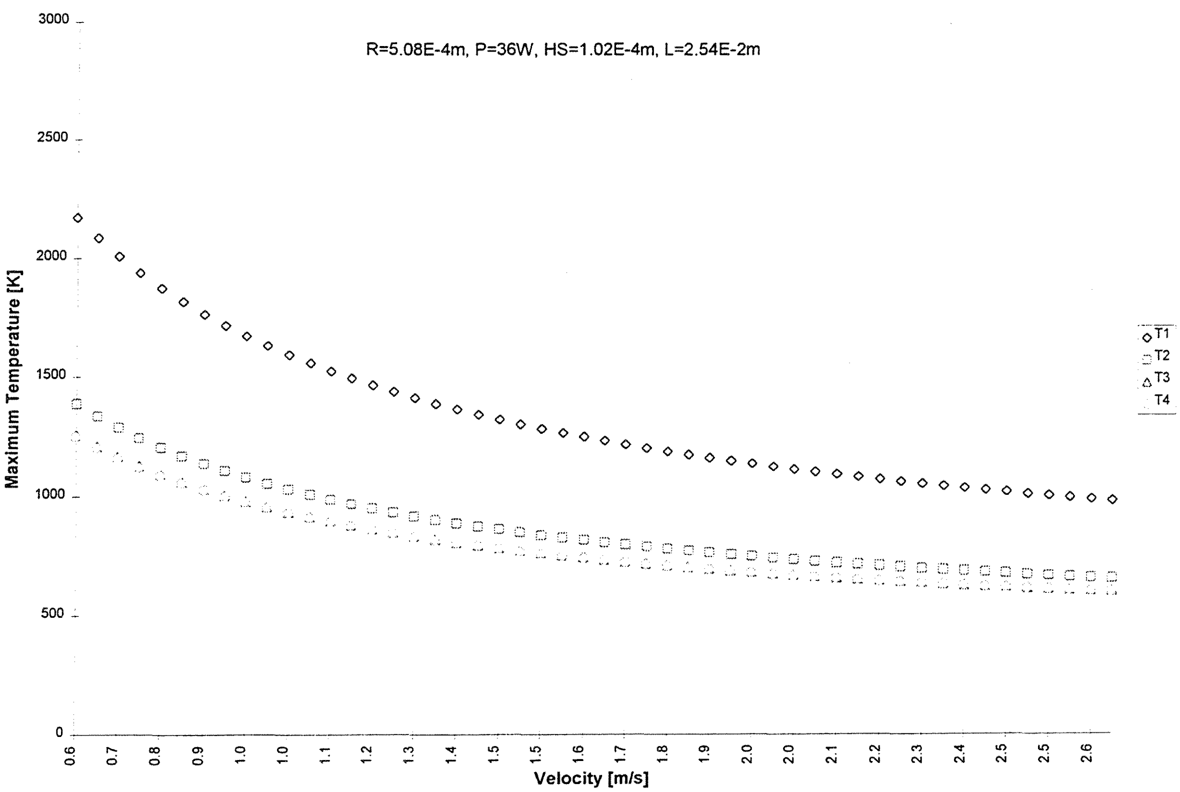

Figure 6. Plot of maximum temperature attained within a layer varying velocity using the large spot size

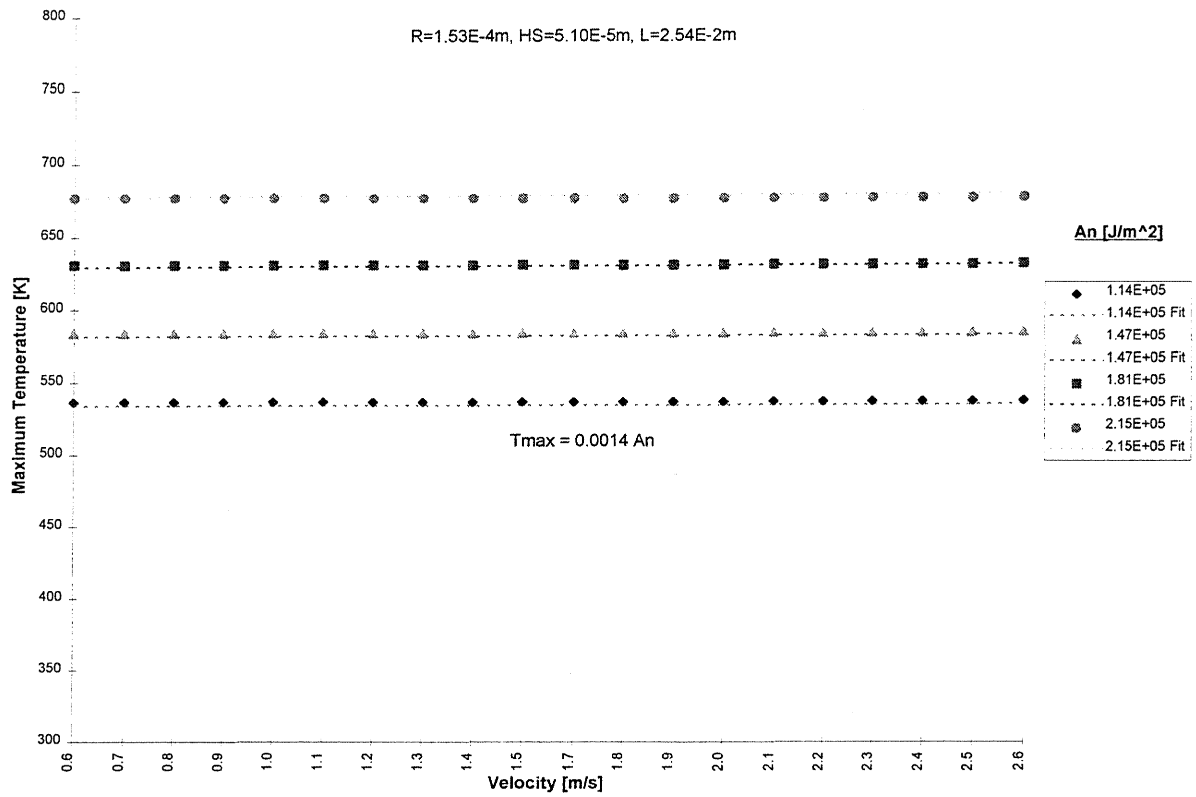

Figure 7. Plot of maximum temperature varying velocity and power for constant energy density using the small spot size

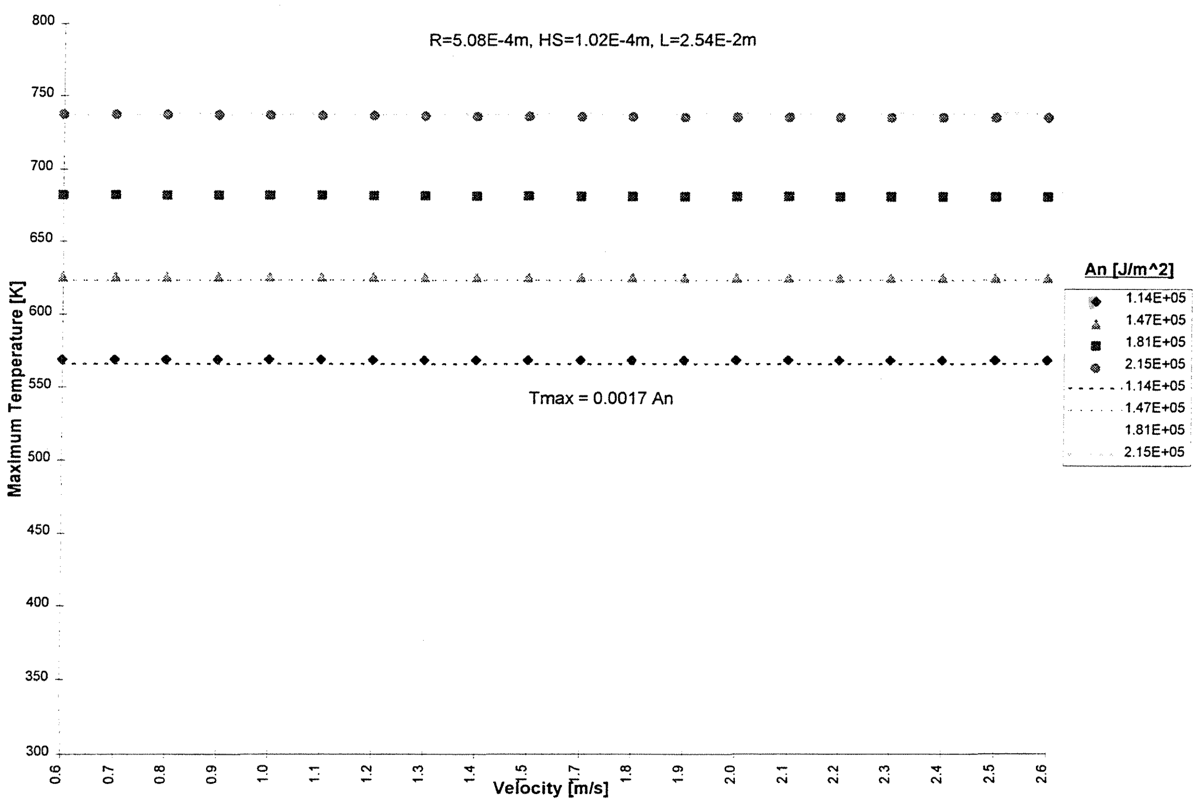

Figure 8. Plot of maximum temperature varying velocity and power for constant energy density using the large spot size