Finite Element Analysis of the SALDVI Process

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Abstract

Selective Area Laser Deposition Vapor Infiltration (SALDVI) is a developing solid freeform fabrication (SFF) technique aimed at the direct fabrication of ceramic and ceramic/metal structures and composites. SALDVI uses a layer-by-layer approach in which layers of powder are densified with solid material deposited from gas precursors by chemical vapor deposition (CVD) using laser heating. In this work, we have performed numerical simulation using the ANSYS code with 3-dimensional coupled field elements to calculate the temperature field and the part geometry resulting from the SALDVI process. The effects of the powder and vapor deposited material properties on the temperature distribution and the part geometry have been investigated. The result from the numerical simulation is found to be consistent with those obtained from experiments performed using the silicon carbide forming gas precursor $Si(CH_3)_4$ and SiC powder particles.

Keywords: Solid freeform fabrication, Finite element modeling, Thermal analysis, SALDVI, Laser densification.

Introduction

Recent advances in physical prototyping allow the production of freeform solid objects directly from a computer model without part-specific tooling and human intervention. These technologies have been termed Solid Freeform Fabrication (SFF). The basic feature of all the SFF techniques is their capabilities to build parts point-by-point and layer-by-layer selectively so that complex-geometry components and systems with highly integrated multifunctions can be fabricated in a single operation. This new manufacturing technology can be used to the direct fabrication of ceramic and ceramic/metal structures and composites. To produce fully functional structural components, powder based approaches to SFF seem to be the most promising [1].

Selective Area Laser Deposition Vapor Infiltration (SALDVI) is such a developing powder-based SFF process in which porous layers of powder are densified by infiltrating the pore spaces with solid material deposited from a gas precursor during laser heating [2]. SALDVI experiments have shown that the size and geometry of the densified part depend in large part on the temperature distribution in the SALDVI workpiece among other parameters [3]. The understanding of the temperature distribution in the SALDVI process is very important to achieve the insight into the effect of various process parameters on the shape of the SALDVI workpiece. During the SALDVI process the relative density of the workpiece continuously changes with processing time until it reaches near full density. Because of such continuous changes in the relative density and thus the continuous change in thermal conductivity of the SALDVI workpiece, the transient temperature field of the SALDVI workpiece is too complex to calculate by analytical methods. Therefore, finite element method (FEM) is used in this paper to quantify the transient temperature distribution and develop fundamental understanding of the formation of the dense part during the infiltration and densification process of the powder bed. Such finite element analyses will certainly provide guidelines for controlling the SALDVI process to fabricate the part with desired geometry and dimensions. Furthermore, these analyses will also be useful for understanding of other SFF processes involving powder-to-dense-body transition such as selective laser sintering (SLS) [4].

Finite Element Model

The goal of this modeling effort is to simulate the densification process of powder bed and evaluate the effect of laser processing conditions on the size and geometry of the dense body resulting from the densification process. The finite element model used for this purpose is shown in Figure 1 and calculated using the ANSYS 3-dimensional coupled-field element (Solid5). The powder bed before densification is assumed to have a dimension of 14-mm length, 7-mm width and 5-mm height. Thus, the powder bed in this study is very thick in comparison with the layer-by-layer fabrication technique, which typically has a powder layer thickness less than 0.5 mm. However, the present simulation allows for assessment of building the first solid layer from a thick powder bed rather than from a thin powder layer on the top of a substrate of different material. Densification of thin powder layer will be modeled in the future effort.

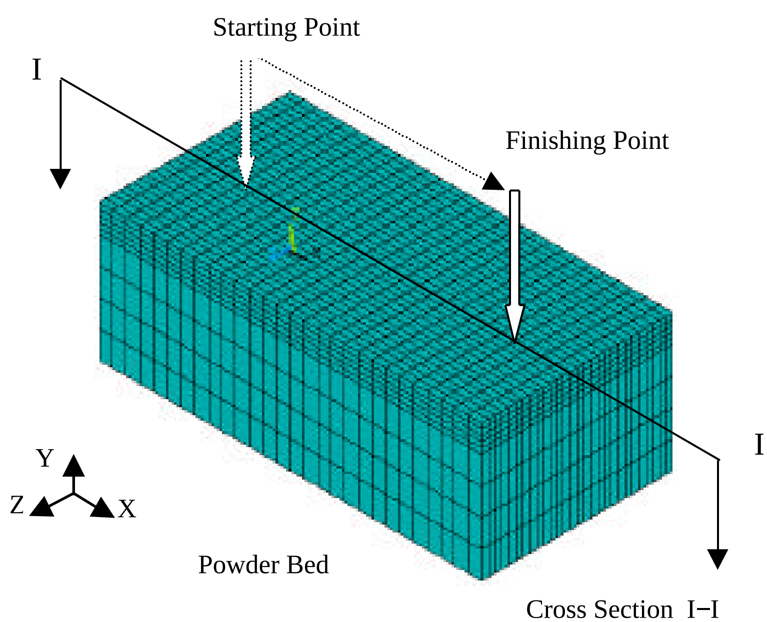


Figure 1. Finite element model of the SALDVI process.

As shown in Figure 1, the SALDVI process is modeled by moving the laser beam from one end of the powder bed to the other and monitoring the temperature change in the powder bed. To simulate the Gaussian-shaped 1-mm diameter laser beam and the infiltration temperature used in the SALDVI experiment, the temperature of the laser beam is fixed at 1353K and the size of the laser beam is 1×1 mm. Since the size of elements in the powder bed at the X-Z plane is

0.5×0.25 mm, there are eight surface elements exposing directly to the laser beam at any given time during the infiltration and densification process. The scanning rate of the laser beam is assumed to be 2.5μm/s and thus the laser beam moves one element distance (0.5 mm) every 200 seconds in the X-direction. The powder bed before laser densification is assumed to have 50% of its theoretic density. When the temperature of an element in the powder bed reaches 1200K, the density of that element is changed to 80% of its theoretic value. It becomes 100% dense when the temperature of the element reaches 1273K. The part being densified is assumed to be in contact with a gas and the heat loss through the gas is approximated through the inclusion of a convection heat transfer coefficient (6×10^{-5} w/mm^2K) between the part and the gas. The temperature of the gas is assumed to be 300K and no temperature dependence of the convection heat transfer coefficient is considered.

The properties of the material used in this simulation are summarized in Table 1 [5] and Table 2 [7-8]. SiC material has been chosen because this simulation can provide direct guidelines for processing of SiC parts using SALDVI and be compared to the experimental result obtained previously [9].

Table 1 Summary of Material Properties of SiC Solid [5]

Temperature(K)	273	473	773	973	1273	1353
Elastic Modulus (MPa)	4.6E5	4.57E5	4.5E5	4.4E5	4.35E5	4.22E5
Thermal Conductivity (W/mm.K)	0.333	0.221	0.137	0.110	0.078	0.063
Specific Heat(J/kg.K)	574	952	1134	1189	1251	1295
Thermal Expansion Coefficient(1/K)	1.9E-6	3.7E-6	4.6E-6	4.9E-6	5.0E-6	5.11E-6
Density(g/cm^3)	3.21					
Poisson's Ratio	0.21					

Table 2 Summary of Material Properties of 50% Dense SiC Powder [6-8]

Temperature(K)	273	473	773	973	1273	1353
Elastic Modulus (MPa)	100	100	100	100	100	100
Thermal Conductivity (W/mm.K)*	1.9E-4	3.2E-4	3.2E-4	3.1E-4	3.3E-4	3.9E-4
Specific Heat(J/kg.K)**	618	984	1134	1193	1266	1309
Thermal Expansion Coefficient(1/K)***	3.3E-6	4.2E-6	4.9E-6	5.3E-6	5.8E-6	6.1E-6
Density(g/cm^3)	1.6					
Poisson's Ratio	0.21					

*50% dense 320 mesh powder in 1 atm. Air (curve 19) [6]
**dense cubic SiC (curve 3) [7]
***dense α−SiC (recommended values) [8]

Results of Finite Element Simulation

The temperature distribution on the surface of the part after one pass of laser scanning from one end to the other is shown in Figure 2. As expected, the temperature of the material within the laser scanning path is higher than that of the rest of the material. Furthermore, the temperature gradient in the material within the scanning path is smaller than that in the material outside the scanning path. This is due to densification of the material within the scanning path, thereby the increased thermal conductivity and low temperature gradient within the scanning path.

The shape of the part that is 100% dense resulting from the same scanning condition as that shown in Figure 2 is presented in Figure 3. It is noted that the cross section of the densified part can be divided into three regions. Region A represents the initial transient region. Region B is the steady state region for the processing condition and the material used in the modeling. Region C is the final transient region. The thickness of the part varies from region to region. Such phenomenon is related to either the change in the thermal conductivity when the powder compact changes to the dense solid, or the difference in heating time. Recall that under the current laser scanning conditions the elements at the two very ends are only subject to 200 seconds of laser heating, whereas all the other elements between the two very ends have exposed to the laser heating for 400 seconds. Thus, the thinner sections in Figure3 at the two very ends compared with their neighboring areas are due to shorter heating time.

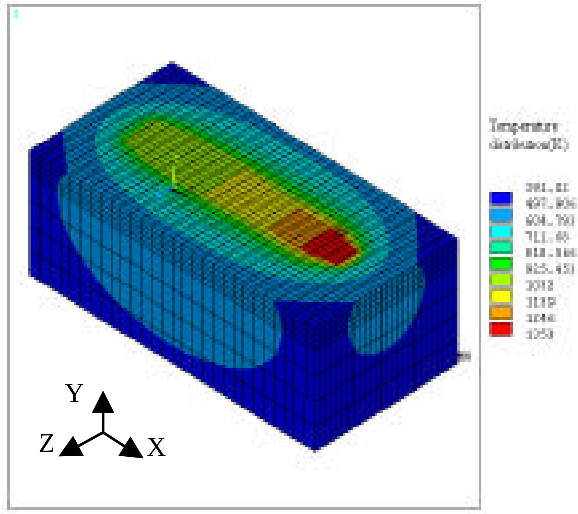


Figure 2. Temperature distribution of the surface of the part after one pass of laser scanning from one end to the other

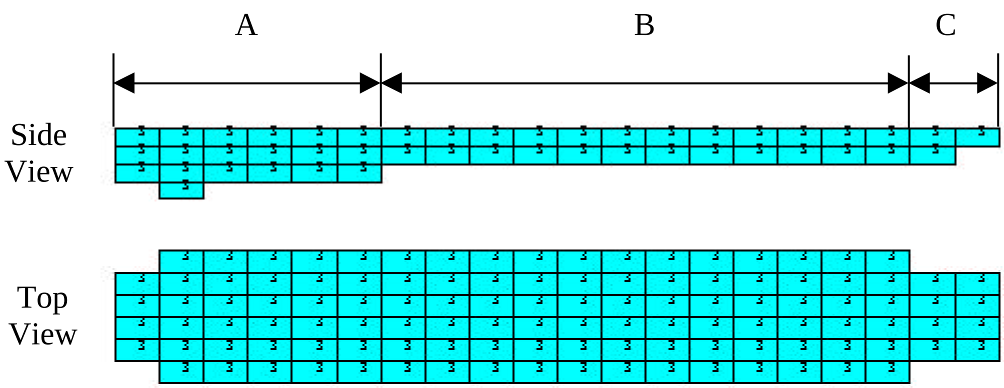
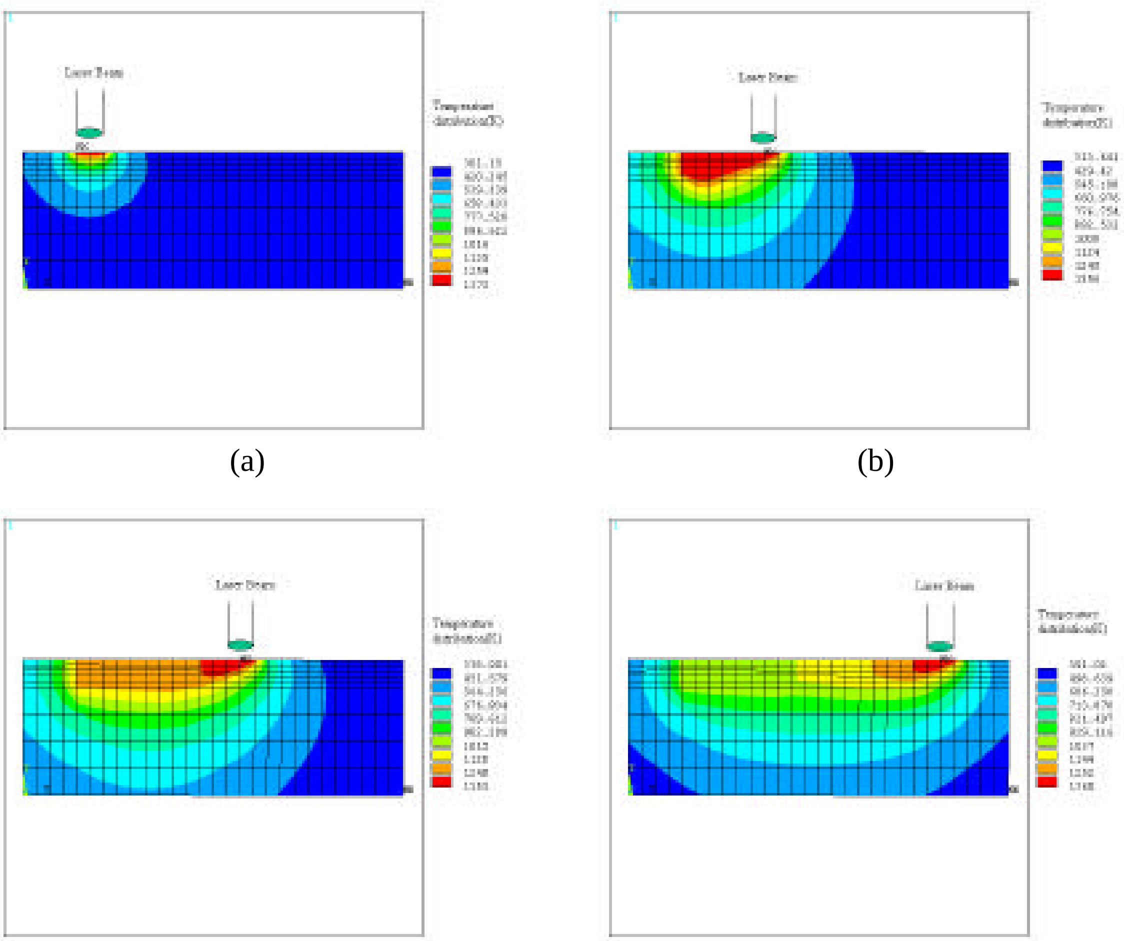


Figure 3. The shape of densified part after one pass of laser scanning

The thickness change between the two very ends can be rationalized as follows. At the beginning of the laser scanning, the laser-heated area is surrounded by powder and heat dissipation is slow. Thus, more heat is available for densifying the powder under the laser beam, thereby a thicker densified section at the beginning of the scanning. As the scanning proceeds, the part size increases and more heat is dissipated through thermal conduction along the previously densified section. Thus, the thickness of the currently densified section becomes thinner than that of the previously densified section (e.g. the last part of Region A vs the thicker part of Region A). Finally, a steady state is reached that heat conduction through the previously densified section does not change much with time (Region B). Since more heat is conducted away through the previously densified section in the steady state region than that in the initial transient region, the thickness of the section in the steady state region is smaller than that in the initial transient region.

The temperature distribution along the cross section I-I of Figure 1 as a function of the laser scanning position is shown in Figure 4 which confirms the aforementioned reasoning. It can be seen that the region with high temperatures (i.e. > 1240K) is thicker during the initial scanning period except the first scanning point, and becomes thinner after that. The shape of the part obtained by the simulation shown in Figure 3 is similar to that obtained by the experiment [9].

This study indicates that in order to fabricate a part with minimum transient regions the infiltration and densification temperature during laser scanning should be adjusted according to heat dissipation as well as energy input. This finding is different from the conventional wisdom that the laser input power should be adjusted to maintain a constant densification temperature during laser densification. This study shows that constant densification temperature produces a constant cross section only when a steady state of heat dissipation and energy input has been reached. At the transient regions the infiltration and densification temperature should be adjusted if the transient regions are to be minimized.



(a) (b) (c) (d)

Figure 4. Temperature distribution in the cross section I-I shown in Figure 1 with (a) at the first scanning point, (b) at about 1/3 scanning distance, (c) at about 2/3 scanning distance, and (d) at the end scanning point

Conclusions

1. An initial and a final transient region are present in the SALDVI workpiece. The thickness of the steady state section is smaller than that in the initial transient section. These phenomena arise from a combined effect of a constant infiltration and densification temperature and a heat dissipation rate that varies with the size of the SALDVI workpiece.
2. Constant surface temperature (e.g. infiltration and/or densification temperature for powder bed) during laser scanning does not provide constant cross section. At the initial and final transient regions not only the laser power but also the densification temperature should be adjusted to minimize the transient regions.

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References

[1] Ashok V. Kumar, Powder Deposition and Sintering for a Two-Powder Approach to Solid Freeform Fabrication, Proceedings of Solid Freeform Fabrication Symposium, David L. Bourell et al. (eds), The University of Texas at Austin, 169-176: 1998

[2] B. R. Birmingham and H. L. Marcus, Silicon Carbide Shapes by Selective Area Laser Deposition Vapor Infiltration, Proceedings of the Solid Freeform Fabrication Symposium, H. L. Marcus et al. (eds), The University of Texas at Austin, 348-355: 1994

[3] J. E. Crocker, L. Sun, H. Ansquer, L. Shaw and H. L. Marcus, Processing and characterization of SALDVI Ceramic Structures, Proceedings of the Solid Freeform Fabrication Symposium, David L. Bourell et al. (eds), The University of Texas at Austin, 495-501: 1999

[4] Hongyun Wang, David L. Bourell, Joseph J. Beaman Jr., Selective Laser Sintering of Quartz Powder, Proceedings of the Solid Freeform Fabrication Symposium, David L. Bourell et al. (eds), The University of Texas at Austin, 465-472: 1997

[5] Web Site "http://www.cvdmaterials.com/sicprop1.htm" from Rohm and Haas Company, USA.

[6] Y.S. Touloukian, R.K. Kirby, R.E. Taylor, and P.D. Desai, Thermophysical Properties of Matter, Volume 2, THERMAL CONDUCTIVITY, IFI/Plenum, New York, New York, 1975

[7] Y.S. Touloukian, R.K. Kirby, R.E. Taylor, and P.D. Desai, Thermophysical Properties of Matter, Volume 5, SPECIFIC HEAT, IFI/Plenum, New York, New York, 1975

[8] Y.S. Touloukian, R.K. Kirby, R.E. Taylor, and P.D. Desai, Thermophysical Properties of Matter, Volume 2, THERMAL EXPANSION, IFI/Plenum, New York, New York, 1975

[9] J. E. Crocker, K. Dai, L. Shaw and H. L. Marcus, A comparison between Experiments and Numerical Simulation of the SALDVI Process, Unpublished Research.