A Theoretical Model for Optimization of SALD Parameters

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Abstract

This paper addresses the need to conduct theoretical work concerning an economical way of Solid Freeform Fabrication rendering by using selective Area Laser Deposition (SALD). The part in SALD rendering process is formed layer by layer that, in turn, is composed of stripes of material produced in the path of a laser. There are three situations in which such a stripe can be rendered: a) alone, b) with one neighbor on one side, and c) with neighbors on both sides. Residual thermal stresses in the part are expected to be affected by how a stripe is rendered. Furthermore, the residual thermal stress and the mechanical property of the part are also dictated by other processing variables such as laser scanning patters, laser input power, scanning speed, scanning spacing, deposition temperature, gas precursor pressure, intrinsic thermal conductivity and mechanical properties of the rendered material. A theoretical approach is proposed to address the minimization of residual thermal stresses and rendering times and the maximization of the strength of the part. It is proposed that such multiple optimizations that are dictated by many decision variables can be solved by minimizing and/or maximizing object functions depending on the design criteria for each attribute of the rendered part.

1. Introduction

Solid Freeform Fabrication (SFF) is advancing very rapidly. Although there still are problems to be solved from the viewpoint of materials science, problems of the design of parts rendered by SFF are more and more in the interest of designers, who have to answer questions of design of machine parts and other shapes to fulfill their functions in optimal ways, mantain required tolerances and desired properties. It is apparent that design for SFF starts at technology level. It is not irrelevant how the part will be rendered [1]. Specifically, for the process of Selective Area Laser Deposition (SALD) [2,3] , a designer has to consider a variety of processing variables that could affect the residual stress and properties of the resulting part. These processing variables include at least laser scanning patters, laser input power, scanning speed, scanning spacing, deposition temperature, gas precursor pressure, intrinsic thermal conductivity and mechanical properties of the rendered material [4].

What values of the processing variables should be selected to achieve the optimization of the rendering process? What would be the proper criteria for the optimization of the rendering process? These questions now stand before designers who are trying to establish some rules and recommendations for SFF fabrication and design that can make the work of designers easier and faster and establish closer cooperation between material and design specialists to solve problems of optimal design of the part not only from functional, but also technological points of view. These issues are addressed in this paper. The model presented proposes optimization of rendering of small plates in an optimal way, according to assumed criteria.

2. Assumptions

The part in the SALD rendering process is formed layer by layer that, in turn, is composed of stripes of material produced in the path of the laser [2]. There are three situations in which such stripes can be rendered. It can be alone, with a neighboring stripe on the one side, or with the neighbors on both sides. If it is rendered alone, the stresses induced by the thermal deformation are small and due only to the different thermal shrinkage between the rendered stripe and the layer underneath the stripe. However, if it is rendered with neighbors on both sides, the stresses will be maximum due to the constraints from both sides as well as underneath. If we imagine cuting a small piece of a stripe in such a worst case, the stress within the stripe due to the constraints can be described by Fig. 1. For the illustration purpose, a simplest possible case is assumed in Fig. 1, that is, the layer deposited is a flat and thin layer. As such, the problem can be treated as two dimensional [1].

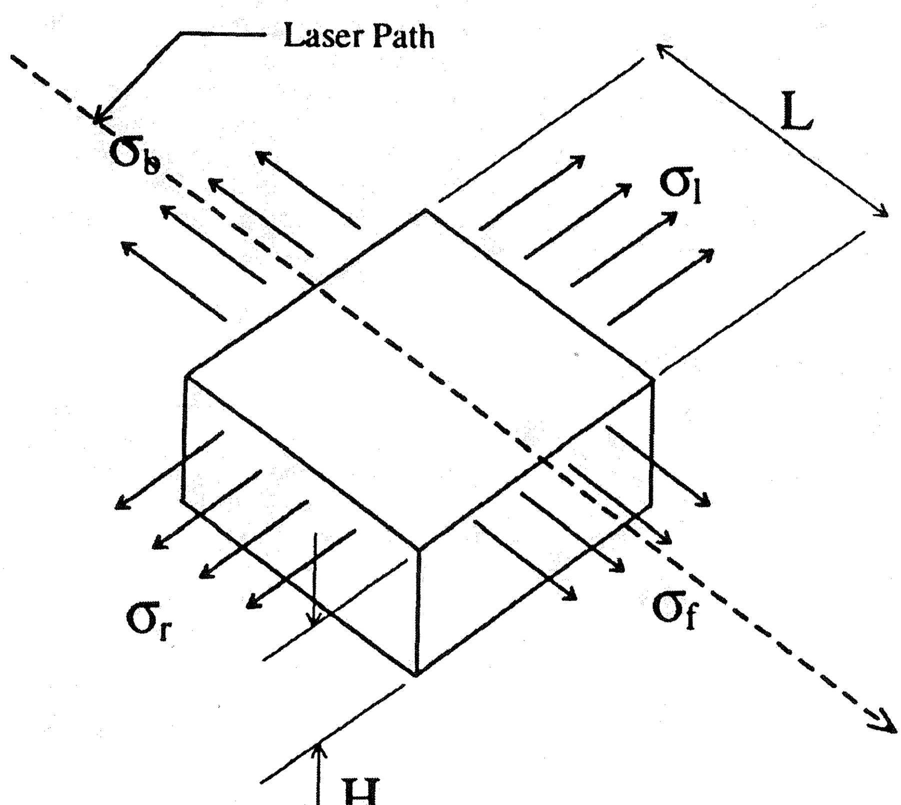

Fig. 1 An idealized elementary block of rendered slice of a part.

3. Thermal Stresses and Deformations

In the dynamic problem of thermoelasticity the heat conduction equation is completed by the equation of motion in displacements [5] in the following way:

$$\sigma_{ji,j}+X_i=\rho u_i^{**} \quad (1)$$

The equation (1) expresses a set of partial differential equations,

where : $$\sigma_{ij}=2\mu\varepsilon_{ij}+(\lambda\varepsilon_{kk}-\gamma T)\delta_{ij}. \quad (2)$$

Expressing the strains in terms of displacements

$$\varepsilon_{ij}=1/2(u_{i,j}+u_{j,i}) \quad (3)$$

and substituting (2) and (3) into (1) one can obtain the following form of equation (1)

$$\mu u_{i,jj}+(\lambda+\mu)u_{j,ji}+X_i=\gamma T_{,i}+\rho u_i^{**} \quad (4)$$

where:

u_i^{**} - second derivative of displacement with respect to time,

ρ - a constant in the following kinetic energy expression $K=\frac{\rho}{2}\int_V v_i v_i dV$,

γ – the quantity appearing in the Duhamel - Neuman relation such that : $\gamma=(3\lambda+2\mu)\alpha_t$,

X_i - represent the mass forces,

$T_{,i}=\delta T/\delta x_i$, (5)

$G=E/2(1+\nu)$ and $G=\mu$ (6)

μ, λ - Lame constants (7)

Equations (1) to (7) express the dynamic problem of thermoelasticity [5] represented in summation notation [6]. If the thickness of the layer is such that the problem should be considered as three dimensional, the equations should be modified by adding components in the direction of Z axis.

Since the conditions will be the most advantageous when the thermal stresses and deformations are minimum, the following object function F expressing thermal stresses and deformations due to the temperature changes can be derived:

$$F(\varphi,k,\omega,v,\delta,p,T) \quad (8)$$

Where: $\varphi(x,y,t)$ – laser pattern function (Fig. 2)
k - thermal conductivity of the rendered layer
ω – laser power
v - scanning speed
δ - scan spacing
p - gas pressure
T – temperature

The equation (8) is written in a general form and can be presented in different ways depending on the specific formulation of the optimization problem as indicated in Section 4.

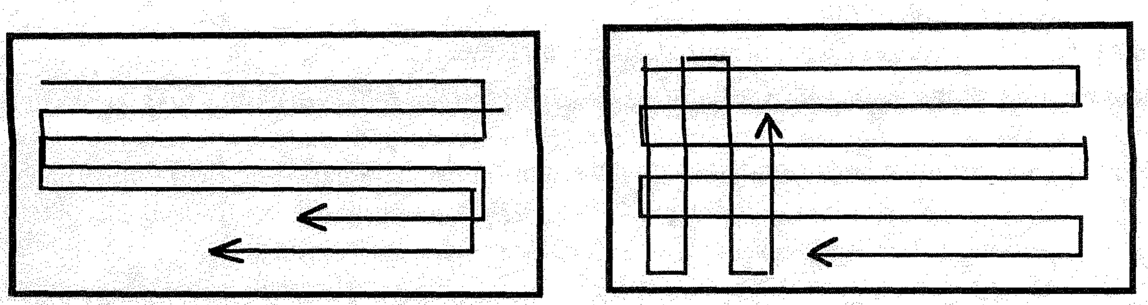

Fig. 2 Examples of the laser pattern working path: (a) parallel scans, and (b) cross scans.

4. Optimization problem in SALD

In this study, it is assumed that rendered elements should be characterized by the following attributes:

-deformation of every layer should be as small as possible,
-the sintered part should have mechanical properties close to the isotropic material,
-the ultimate strength for tension should be as large as possible,
-the time necessary to render every layer should be as large as possible.

To satisfy these requirements, the following criteria for the four -criterion (A, B, C, and D) optimization are assumed:

A -the vertical deformations of any layer of the material and deformations resulting from fabrication of that layer should be minimal

$$F_A = \int_S w^2 = F_A^{min} \qquad (9)$$

where w is the vertical deformation and S the area of the rendered plate.

B -the difference of the constants μ (or E - Young Modulus) in the two orthogonal directions should be minimal:

$$F_B = \mu_x - \mu_y = F_B^{min} \qquad (10)$$

C -the ultimate strength σ_u for tension

$$F_C = \sigma_u = F_C^{max} \qquad (11)$$

D -minimum time needed to render the layer i of the part:

$$F_D = \frac{S_i}{\delta \tilde{v}} = F_D^{min} \qquad (12)$$

where:

S_i - the area of the layer i,

$\tilde{v}$ - the average velocity of the laser,

δ - the width of the material strip rendered with single pass of laser.

The decision variables are: $\varphi(x,y,t)$, ω, v, T, k, δ and p, as defined in equation (8). Note that the decision variables are functions or parameters of the material used to render the element and characteristics of the laser. Further, the decision variables have to comply with the following constraints:

$$\delta \int_S \varphi(x,y,t)dS = S \qquad (13)$$

$$\underline{\omega} \le \omega \le \overline{\omega} \qquad (14)$$

$$v \le \overline{v} \qquad (15)$$

$$\tilde{v} = \frac{v_1 L_1 + v_2 L_2}{L_1 + L_2} \qquad (16)$$

where:

L_1 - the length of the longer laser path (Fig. 3),

L_2 - the length of the shorter laser path (Fig. 3),

$\underline{\omega}$ and $\overline{\omega}$ -the maximum and minimum laser powers,

$\overline{v}$ – the maximum laser scanning speed,

v_1 and v_2 – the laser scanning speed along L_1 and L_2, respectively.

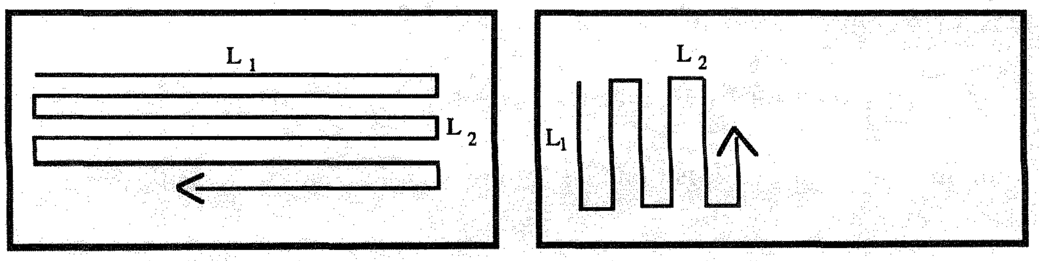

Fig. 3 Horizontal and vertical laser patterns

Physically, the constraint (13) means that the length of the laser path times the width of the rendered strip should cover the entire area of the layer and cannot pass through the path vector more than once. The constraint (14) means that the working laser power has to be included between the maximum and minimum possible powers. The constraint expressed by equations (15) and (16) means that the working velocity of the laser has to be smaller than the maximum possible velocity and that the average velocity of the laser is composed of the velocity on the longer and shorter part of the laser path (Fig. 3).

5. Proposed Optimization Problem Solution

The solution to the problem formulated above is a multicriteria optimization task [7]. It can be achieved in the following steps:

1) The ideal point should be found. To find such apoint, the extreme of all object functions F_A to F_D should be satisfied.

2) Such set of compromises should be found. This means such a domain in which no one of the object functions can be improved without spoiling the other must be found.

3) The solution could be found using one of the methods proposed by C.L. Hwang [8].

In order to find the preferred solution of the problem, we will introduce dimensionless object functions, Φ_i, such that:

$$\Phi_i = \frac{F_i}{F_i^-} \qquad (17)$$

where: $i = A, B, C, D$ and $\Phi_i \leq 1$ and F_i^- is the maximum value of the function F_i which belongs to the set of compromises. The introduction of the dimentionless object function is to facilitate the founding of the preferable solution.

The preferable solution can be found using one of the two approaches:

(a) by method of utility function, (b) by method of matrix function.

Looking for the preferable solution by method of utility function, one has to assign to every dimentionless object function Φ_A, Φ_B, Φ_C and Φ_D a coefficient of importance α, such that

$$\alpha_A + \alpha_B + \alpha_C + \alpha_D = 1 \qquad (18)$$

and create a substitution object function such that

$$\Phi = \alpha_A\Phi_A + \alpha_B\Phi_B - \alpha_C\Phi_C + \alpha_D\Phi_D \qquad (19)$$

and find the minimum value of that function. The minus sign in front of α_C indicates that we are looking for the maximum but not minimum of the function Φ_C.

If we are looking for preferred solution by matrix function method, we have to find the point that belongs to the compromise domain and is located as close as possible to the ideal point. In order to do this, we have to define a function

$$\Phi = (\Phi_A - \Phi_A^{id}) + (\Phi_B - \Phi_B^{id}) + (\Phi_C + \Phi_C^{id}) + (\Phi_D - \Phi_D^{id}) \qquad (20)$$

and find its minimum.

In the cases of only two object functions the solution can be found in the way shown on Fig. 4. As the Fig. 4 shows the preferable point is found as a result of a compromise between F_A^{min} and F_B^{min}.

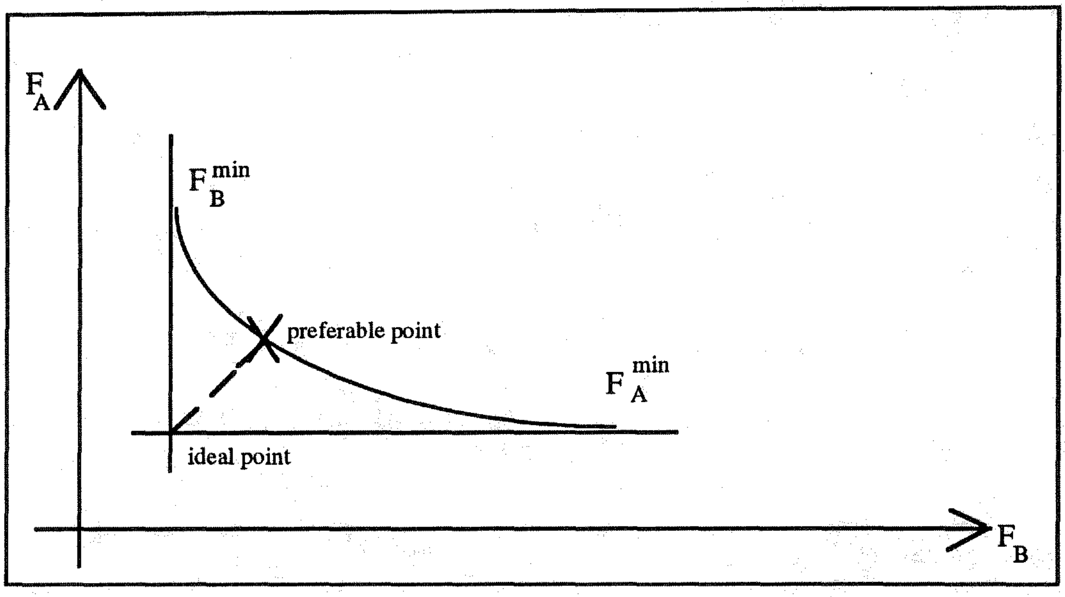

Fig. 4 Solution of the multicriteria optimization problem in the case of two object functions

6. Concluding remarks:

In order to make it possible to find the solution in the way proposed above, it is necessary to know how the object functions depend on the decision variables. The expressions of Φ_A, Φ_B, Φ_C and Φ_D as functions of the decision variables can be developed on the basis of theoretical or empirical findings. In the case described above, it will be necessary to continue the theoretical derivations and empirical tests and describe the object functions as an exact expression, and approximations of the empirical results by polynomials of approved order.

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