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STUDY OF HEAT TRANSFER MECHANISMS DURING THE LENS^{TM} PROCESS

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ABSTRACT

A two-dimensional finite element model was developed to calculate the temperature distribution in the deposited metal during the LENS^{TM} rapid fabrication process. Numerical simulations are performed on the upper region of a thin plate 316 stainless steel part, where experimental data indicates that a uniform temperature can be assumed at the base of this region. The time evolutions of the isotherms are calculated as the laser beam travels across the top surface of the part. The model dynamically updates the thermal boundary conditions with laser position, so it is able to calculate temperature profiles both far of and near the side edges of the plate. The effective laser power is determined by matching predicted with previously measured maximum temperature in the molten pool. Good agreement is obtained between the calculated and the measured temperature profiles. The model is then used to investigate the relative importance of different mechanisms of heat transfer (conduction, convection, and radiation) during the process. It is found that the heat loss by convection and radiation from the part surface is not significant and that most of the deposited laser energy is transported away from the molten pool by thermal conduction through the part.

KEYWORDS: Modeling, LENS, laser welding, thermal profiles

1. INTRODUCTION

Laser Engineered Net Shaping (LENS^{TM}) is a rapid fabrication process in which three-dimensional metal structures are built layer by layer from computer aided designs. In this process, a laser beam is focused onto a substrate to create a molten pool in which powder particles are simultaneously fed. The substrate is moved beneath the laser beam under the computer guidance to deposit a thin cross section, creating the desired geometry for each layer. Starting from the bottom of the part, one layer is produced at a time. After deposition of each layer, the powder feeding nozzle and laser beam assembly is moved in the positive Z-direction, thereby building a three-dimensional component layer additively.

The LENS process has the potential to dramatically reduce the time and cost required to fabricate functional metal parts. Since mechanical properties are dependent upon the microstructure of the material, which in turn is a function of the thermal history of solidification, an understanding of the thermal behavior of the fabricated part during the LENS process is of special interest. Unlike other laser processing techniques, LENS uses relatively low power lasers which produce a very small heat-affected zone (HAZ). In typical applications to steel alloys, the laser power is 300 – 500 W, the substrate traverse velocity is about 8 mm/s, and the volume of the molten pool is about 0.5 mm^3 [1].

Hofmeister et al [1] and Griffth et al [2] performed experiments using ultra high speed digital imaging techniques during the LENS process, providing valuable information on the characteristics of the temperature profile, molten pool size, thermal gradients and cooling rates around and in the molten pool of 316 stainless steel (SS316) plate samples. In these experiments, the temperature along the axis of the plate was extracted from the thermal images and the temperature gradient along the travel direction was obtained. We used these experimental data to calibrate the model developed in this work.

Very few simulation works on the thermal behavior in the LENS process have been conducted in the past [1-3]. These studies estimated that most of the deposited laser energy was conducted through the substrate, and the contributions of other possible forms of heat transfer, such as heat convection and radiation from the surface of the deposited material were negligible. However, neither experimental measurements nor numerical predictions have confirmed this statement. A detailed study is necessary to investigate the importance of heat convection and radiation from the surface of the deposited material.

In this paper, a two-dimensional thermal model is developed to predict the temperature distribution in the deposited SS316 during the LENS process as a function of time and process parameters. The maximum temperature in the molten pool measured in the experiments by Hofmeister et al. [1] was used to calibrate this model. In addition, test simulations for moving heat sources were verified against an existing analytical solution in the literature [4]. The relative significance of the different forms of heat transfer, including heat conduction, convection, and radiation from the surface of the deposited material is then quantitatively investigated.

2. MATHEMATICAL MODEL

Numerical simulations are performed in the upper region of a thin plate fabricated by the LENS process, where experimental data indicates that a uniform temperature can be assumed at the base of this region [1]. Figure 1 shows the schematic of the two-dimensional model used in the present work.

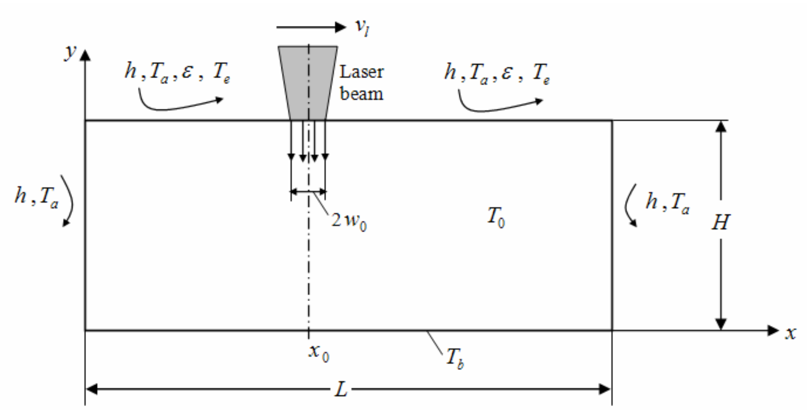


Figure 1 - Schematic of the model used for predictions on the temperature distribution of the LENS-fabricated sample

The model uses a 25×10 mm rectangular computational domain. A laser beam of power P_l and radius w_0 moves from left to right along the top edge of the computational domain at a travel velocity v_l (in the actual process, it is the part which moves and the laser stays fixed). The power-intensity distribution in the laser-beam cross section is assumed to be given by the following Gaussian function [5]:

$$I(x-x_0) = I_0 \exp\left(-\frac{2(x-x_0)^2}{w_0^2}\right) \tag{1}$$

where x_0 is the x coordinate of the laser-beam axis and I_0 is the maximum power intensity defined as:

$$I_0 = \frac{2P_l}{\sqrt{2\pi} w_0} \tag{2}$$

The thermal model uses the finite element method to numerically solve the following two-dimensional energy conservation equation:

$$\frac{\partial T}{\partial t} = a\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) - \frac{L}{C_p}\frac{\partial \phi}{\partial t} \tag{3}$$

where T is temperature, t is time, a is the thermal diffusivity, L is the latent heat of melting, C_p is the specific heat, and ϕ is the volume fraction of liquid, approximated as:

$$\phi \approx \frac{T - T_s}{T_l - T_s} \tag{4}$$

where T_l is the liquidus temperature (1733 K), and T_s is the solidus temperature of the alloy (1693 K).

The initial condition in the computational domain is set corresponding to a uniform temperature field equal to the temperature at the base of the modeling region. The boundary conditions are defined as follows. Along the top edge of the computational domain, the following convective and radiation-based heat flux condition is used:

$$-k\frac{\partial T}{\partial y} = h(T - T_a) + \varepsilon\sigma\left(T^4 - T_e^4\right) \tag{5}$$

where k is the thermal conductivity, h the convective heat transfer coefficient, T_a the ambient temperature around the part, ε the emissivity of the part surface, σ the Stefan-Boltzmann constant [σ = 5.67×10^{-8} W/m^{2}K^4], and T_e the temperature of the internal wall of the glove box (taken equal to T_a in this work) .

A convective boundary condition is imposed on both vertical sides of the part and given by:

$$-k\frac{\partial T}{\partial x} = h(T - T_a) \tag{6}$$

The bottom of the computational domain is subjected to the dirichlet boundary condition:

$$T = T_0 \tag{7}$$

with T_0 a uniform temperature taken from the experiments of Hofmeister et al [1].

The top edge of the computational domain beneath the laser beam is subjected to the following heat-flux boundary condition:

$$-k\frac{\partial T}{\partial y} = \alpha I(x - x_0) \tag{8}$$

where α is the effective absorption of the laser beam energy. After substitution of Eqs. (1) and (2) into (8) and rearrangement, the prescribed normal temperature gradient on the top surface under the beam can be written as:

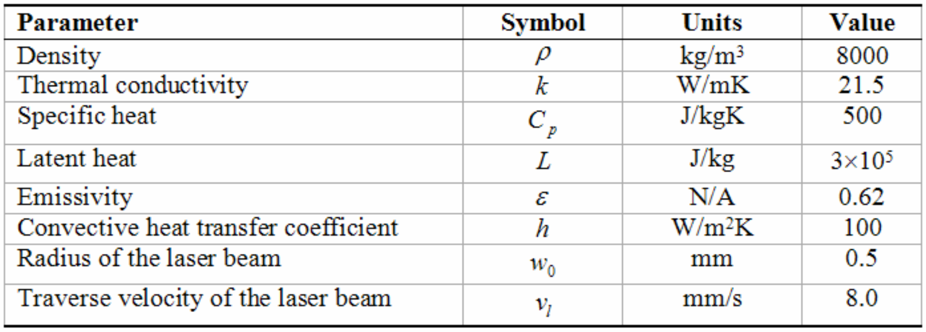
$$\frac{\partial T}{\partial y} = -\frac{\alpha I_0}{k}\exp\left(-\frac{2(x - x_0)^2}{w_0^2}\right) \tag{9}$$

Note that x_0 in Eq. (9) is a function of time, travel velocity of the laser beam, and the initial position of the laser beam relative to the computational domain.

3. RESULTS AND DISCUSSION

The calculations of temperature distribution in a fabricated SS316 alloy plate during the LENS process are compared with measurements of thermal profiles done by Hofmeister et al [1]. In those experiments, ultra high speed digital imaging techniques were employed to show the image of the molten pool and the temperature distribution on the surface surrounding the molten pool. The details of the experimental setup can be found in that reference. For the purpose of comparing calculated and experimental data, similar computational parameters as that in Ref. [1] are used, which are shown in Table I.

Table I. Material Properties for 316 Stainless Steel and LENS Process Parameters [1]



Parameter	Symbol	Units	Value
Density	ρ	kg/m^3	8000
Thermal conductivity	k	W/mK	21.5
Specific heat	C_p	J/kgK	500
Latent heat	L	J/kg	3×10^5
Emissivity	ε	N/A	0.62
Convective heat transfer coefficient	h	W/m^{2}K	100
Radius of the laser beam	w_0	mm	0.5
Traverse velocity of the laser beam	v_l	mm/s	8.0

The computational domain is divided into 500×200 bilinear finite elements, yielding $\Delta x = \Delta y = 5.0\times10^{-5}$m. This mesh was used throughout the present study. The convergence of the mesh was checked against finer discretizations without noticeable change in the results.

Figure 2 provides a comparison of measured and calculated thermal profiles on the top surface of the sample from the center of the molten pool along the travel direction of the sample. The calculated values are taken when the beam is at the center of the part and side effects can be neglected. The experimental data of Ref. [1] was used to adjust the effective power level of the laser, plus a uniform temperature at the base of the domain T_0 = 1350K. This temperature was measured by Hofmeister at al [1] for a nominal laser power of 275W. The boundary conditions include a convective heat loss with h = 100 W/m^{2}K and T_a = 303K from the top and side boundaries of the part. The transient simulation was started from a uniform initial temperature equal to the base temperature. It is observed from Fig. 2 that the calculated temperature profile follows rather well the experimental data.

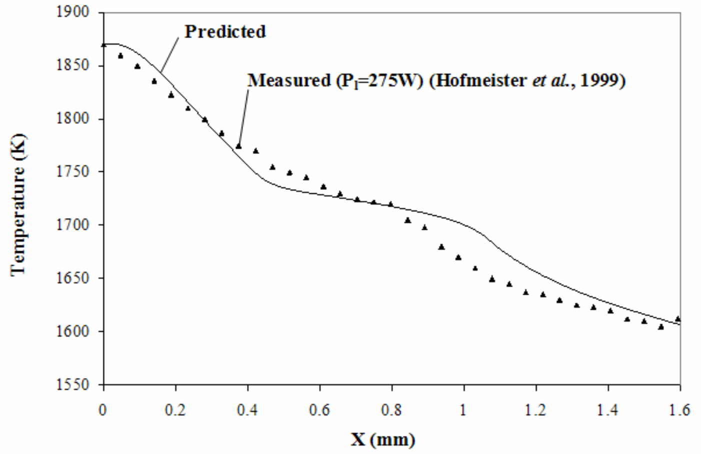


Figure 2 - Comparison of predicted and measured thermal profiles on the top surface of the sample from the center of the molten pool along the travel direction of the sample (SS316)

The calibrated model was then used to calculate the heat loss due to both convective heat transfer and radiation along the top surface of the sample. The results are shown in Figure 3, for the same power settings as the previous simulation. It can be seen that the heat flux due to convection does not change much along the surface, although the magnitude surrounding the molten pool is slightly higher than that in other locations. However, the heat flux due to radiation from the molten pool is significantly higher than that in both sides away from the molten pool. After integration along the top surface, the total heat loss due to convective and radiative heat transfer can be calculated at 7.5W if the thickness of the sample is taken as 1 mm (approximately the plate thickness of Hofmeister's experiments). Therefore, for a total laser power of 275W and an absorption coefficient of the laser beam of 0.3 [5], about 9.1% of the heat is dissipated due to convection and radiation, while the rest is conducted through the fabricated part. This result is consistent with estimates by other investigators [1], and provides a quantitative confirmation that most of the laser energy is conducted through the part while the heat loss by surface convection and radiation is not significant.

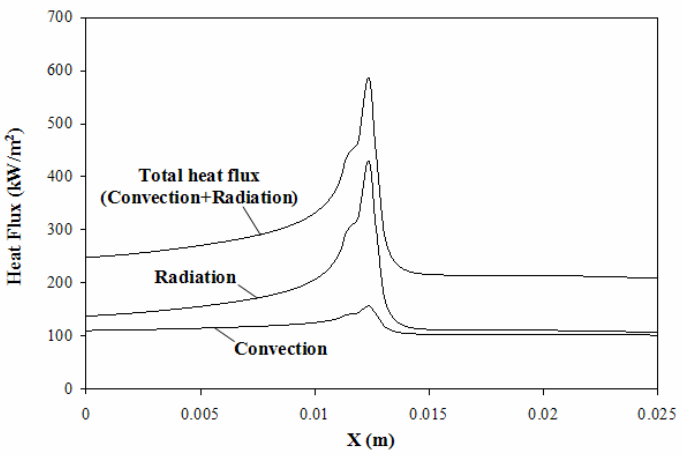


Figure 3 - Heat flux due to convection and radiation along the top surface of the sample

4. CONCLUSIONS

A finite element model was developed to calculate the temperature distribution in SS316 plates during fabrication by the LENS process. The model predicts a temperature profile along the molten pool region that agrees qualitatively and quantitatively well with measured data. The model was used to study the relative importance of different heat transfer mechanisms. It was found that about 90% of the deposited laser energy is transported away from the pool by thermal conduction through the part, in agreement with estimations done by previous works, but that had never been confirmed experimentally or numerically. This observation has important consequences in guiding the computational modeling of the LENS process. In particular, the numerical predictions are highly sensitive to the value of the thermal conductivity and its dependence with temperature. Reliable measured data of the thermal conductivity at high temperature is necessary for accurate predictions of the thermal aspects of the process.

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