

Parametric Analysis of Pulsed Laser Melting Process

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Abstract. An axisymmetric numerical model has been developed to study the laser drilling of a cylindrical work piece under repetitive Gaussian laser pulse. Finite volume method has been used to discretize the energy equation. Convective and radiative heat losses have been considered from the laser irradiated surface. The resulting algebraic equation has been solved with the help of Tri-Diagonal Matrix Algorithm (TDMA) to know the temperature distribution in the work piece. The enthalpy porosity method has been employed to capture the moving solid-liquid interface evolving due to melting of the work piece subjected to laser energy. The laser source irradiated on the work piece has been considered as volumetric laser source instead of surface laser source which is rarely found in the existing literature. The present model is validated first with the existing literature. It has been found that, the results agree well. A parametric analysis has been done to know the effects of different laser parameters such as duty cycle, energy, pulse width and frequency etc. on the temperature field and the size of the melt pool when the work piece is subjected to repetitive laser pulse. The numerical results can provide some guidance for practical laser drilling process.

Nomenclature

a_0	beam radius
C_p	specific heat
g_L	liquid mass fraction
h	convective heat transfer coefficient
h_{sen}	sensible heat
H	total enthalpy
k	thermal conductivity
I_0	peak intensity of laser beam
L_f	latent heat of fusion
ms	millisecond
n	number of pulses
S_{LS}	volumetric laser source term
S_h	enthalpy source term
T	temperature
t	time
t_{on}	ON-time of laser
t_{off}	OFF-time of laser
r, z	coordinate directions
R	radius of the workpiece
L	length of the workpiece

Greek Symbols

α	thermal diffusivity
λ	under-relaxation factor
σ	Stefan-Boltzmann constant
Δt	size of time step
ΔV	volume of control volume
ΔH	nodal latent heat
τ	pulse width
κ	absorption coefficient

Subscripts

m	melting point
P	control volume
S	solid phase
L	liquid phase

Superscripts

n	number of iteration
0	previous time step



1. Introduction

Materials with better mechanical properties have been developed in the recent years with gradual progresses in the fields of metallurgy and material science. The traditional machining processes are not adequate enough to machine these materials properly with better accuracy and precision. Therefore, non-traditional machining processes have been developed and among these processes laser machining process has received better response from the manufacturers because of its accuracy, precision and better handling ability of the machined materials. In order to improve the performance of laser machining process, it is important to understand the laser-material interaction.

Many researchers have conducted research studies to find out the influence of various laser parameters such as peak intensity, laser energy, pulse width, duty cycle, frequency, beam radius etc. and the physical properties of the materials being machined on the laser machining process, material removal rate, type of surface being generated and grain structure following the machining process. Brent et al. [1] developed the enthalpy-porosity technique to track the solid-liquid interface during the melting of a pure metal. Basu and Srinivasan [2] investigated the effects of convection on laser melting and studied how convection changes the melt pool shape. Chen et al. [3] conducted laser heating under repetitive pulse and studied variation in temperature with radial and axial length of the workpiece model and with variations in duty cycle and frequency of the laser source. Kar and Rath [4] investigated the effect of natural convection on the shape of melt metal pool developing a two dimensional axisymmetric numerical model based on one-phase continuum mixture theory and fixed grid technique for both single and repetitive laser pulse. Qin et al. [5] developed a semi-infinite axisymmetric model to study the melting process in a metal slab subjected to Gaussian laser pulse.

In the current work, an axisymmetric numerical model has been developed. First, the model has been validated with the existing literature and then the study has been extended to investigate the effects of the laser parameters like peak intensity, energy, pulse width, duty cycle and frequency on the performance of laser melting.

2. Physical Model

A two-dimensional axisymmetric geometry has been developed for the parametric study of laser melting of a cylindrical workpiece. The laser source, being irradiated on the work surface is Gaussian in spatial variation and square in temporal variation as shown in the Figure. 1a. The schematic and computational domains have been shown in the Figure.1b. The workpiece is assumed to be at a uniform initial temperature of T_0 . The laser irradiated surface is subjected to convective and radiative boundary condition while the rest of the two surfaces are being subjected to insulated boundary conditions. The radius of the workpiece has been taken as 5mm while the length has been taken as 2mm. Aluminium has been taken as the material of the workpiece. For simplifying the study, certain assumptions have been made. The thermo-physical properties of aluminium have been considered as constants, but different values have been taken for solid and liquid phases. Boussinesq's approximation holds good for density change with temperature. The laser source has been considered as volumetric in nature. Both the workpiece and laser source are assumed to be stationary. Metal removal occurs only through melting and vaporization has been avoided during the machining process. After the consideration of the above assumptions, the governing differential equations and boundary conditions have been defined.

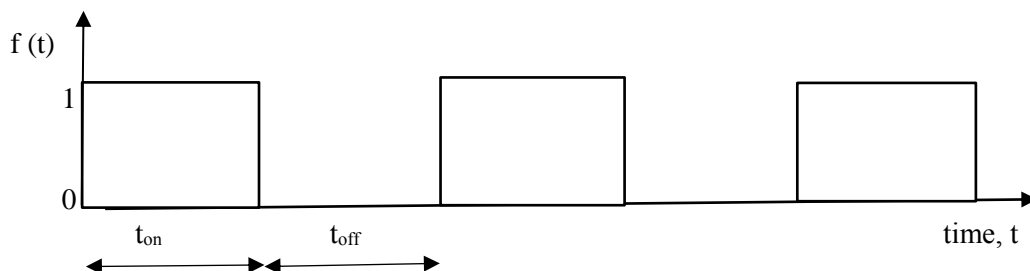


Figure 1(a). Temporal variation of laser intensity for repetitive pulse.

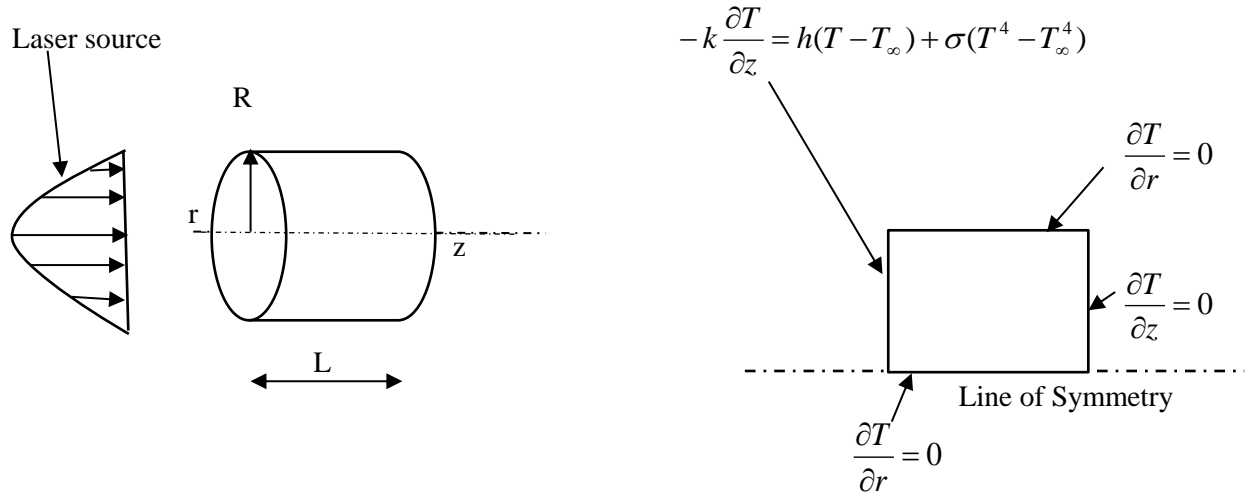


Figure 1(b). Schematic and computational model.

Governing Equations:

Energy Equation:

$$\frac{\partial}{\partial t}(\rho H) = \frac{\partial}{\partial z}(\rho \alpha \frac{\partial h_{sen}}{\partial z}) + \frac{1}{r} \frac{\partial}{\partial r}(\rho \alpha \frac{\partial h_{sen}}{\partial r}) + S_{LS} \quad (1)$$

$$\frac{\partial}{\partial t}(\rho C_p T) = \frac{1}{r} \frac{\partial}{\partial r}(kr \frac{\partial T}{\partial r}) + \frac{\partial}{\partial z}(k \frac{\partial T}{\partial z}) + S_h + S_{LS} \quad (2.1)$$

$$S_h = -\rho_L L_f \frac{\partial g_L}{\partial t} \quad (2.2)$$

Initial Condition:

$$T(r, z, 0) = T_0 \quad (3.1)$$

Boundary Conditions:

$$\text{Right wall: } -k \frac{\partial T(r, L, t)}{\partial z} = 0 \quad (3.2)$$

$$\text{Top surface: } -k \frac{\partial T(R, z, t)}{\partial r} = 0 \quad (3.3)$$

$$\text{Bottom surface (Symmetry): } \frac{\partial T(0, z, t)}{\partial r} = 0 \quad (3.4)$$

$$\text{Left wall: } -k \frac{\partial T(r, 0, t)}{\partial z} = h(T(r, 0, t) - T_\infty) + \sigma(T^4(r, 0, t) - T_\infty^4) \quad (3.5)$$

Equation (1.1) is applicable both to the solid and liquid phases and also the interface that defines the movement of solid-liquid interface. When the laser is ON, the value of $f(t)$ is 1 while it is zero when the laser is OFF.

3. Numerical Method

The finite volume method (FVM) described by Patankar [6] has been used to discretize the equation 2.1. The resulting algebraic equations are solved using a line-by-line Tri-Diagonal Matrix Algorithm. The latent heat content has been used to capture the solid-liquid interface during melting. The iterative liquid volume fraction update equation of g_L for a control volume can be written as follows.

$$g_L^{n+1} = g_L^n + \lambda \frac{a_p \Delta t}{\rho_L L_f \Delta V_p} (T_p^n - T_m) \quad (4)$$

A control volume is considered to be completely melted when $g_L = 1$. The convergence criteria of the iterative solution has been set to 10^{-6} in the present simulation.

4. Results and discussion

The present numerical model has been validated with the existing result from the literature [3]. The temperature at the centre of the work piece at different heating time has been plotted as shown in the Figure 2. The properties of the material of the workpiece and different laser parameters have been taken as per the literature. The result of the present model agrees well with the analytical solution found in the existing literature. Therefore, the study with the help of the existing model has been extended further.

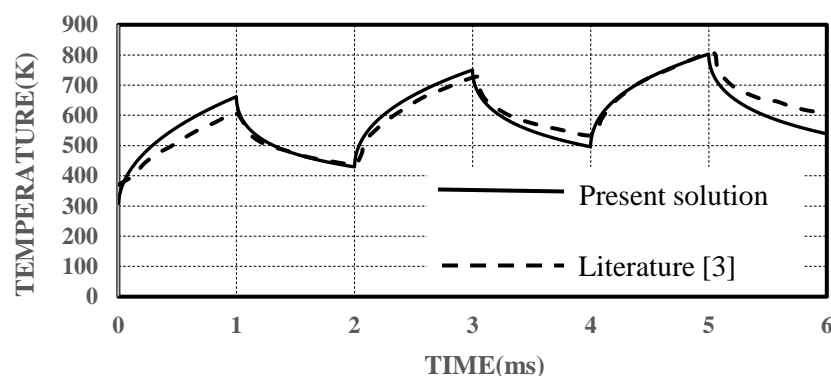


Figure 2. Comparison of temperature distribution at the centre of the workpiece with literature [3].

For the current analysis, repetitive laser pulse has been taken into consideration here. The total time of application of laser is 10ms and the number of pulses is 5. Total laser energy has been taken as 4J and frequency is 500Hz. By varying the duty cycle of the laser source as 0.25, 0.50 and 0.75, the ON and OFF- time and the peak intensity of the laser have been varied. The properties of aluminium have been taken from literature [5]. The laser beam radius has been taken as 700 μ m and initial temperature of the workpiece has been taken as 300K.

When the laser is ON, temperature at the point of laser application increases and decreases when laser is OFF. For the smallest duty cycle, the rise in temperature is the greatest because of the maximum peak intensity at constant energy. When duty cycle decreases, the OFF-time of laser increases that causes lowest final temperature for the lowest duty cycle. The final temperature after total heating is the highest for the maximum duty cycle which has been shown in the Figure 3. With increase in laser energy, the maximum temperature attained during heating increases.

With the laser irradiation at the centre of the workpiece, aluminium starts melting and with progress in heating period, the amount of metal removed increases which is evident from the outward movement of the liquid-solid interface with time as shown in the Figure 4.

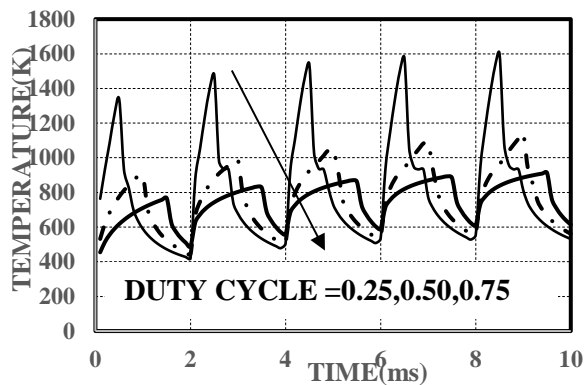


Figure 3. Variation of centre temperature with duty cycle.

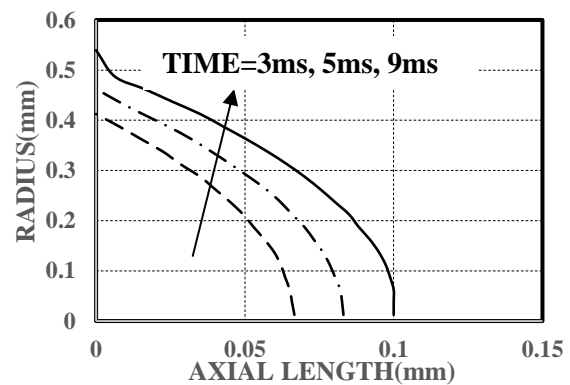


Figure 4. Movement of solid-liquid interface with time.

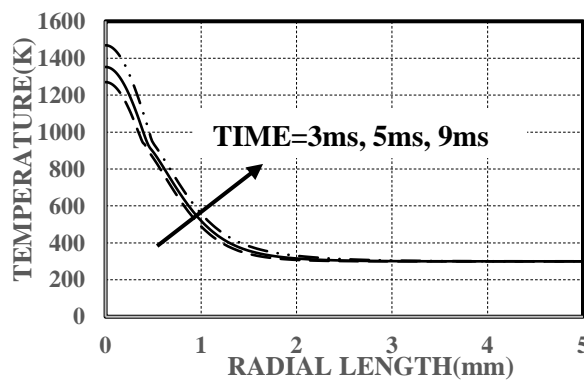


Figure 5. Variation of radial temperature with time.

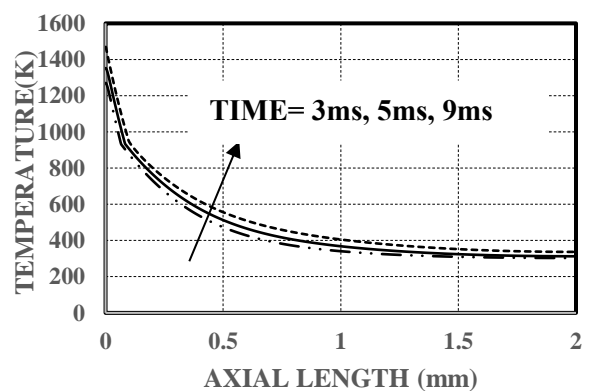


Figure 6. Variation of temperature along the axis of symmetry with time.

The workpiece was initially at 300K temperature. With heating, temperature at the point of application increases highly and conduction causes rise in temperature in the neighbouring points both in the radial and axial directions as shown in the Figure 5 and Figure 6 respectively, but beyond a certain distance from the point of application, the initial temperature is not disturbed.

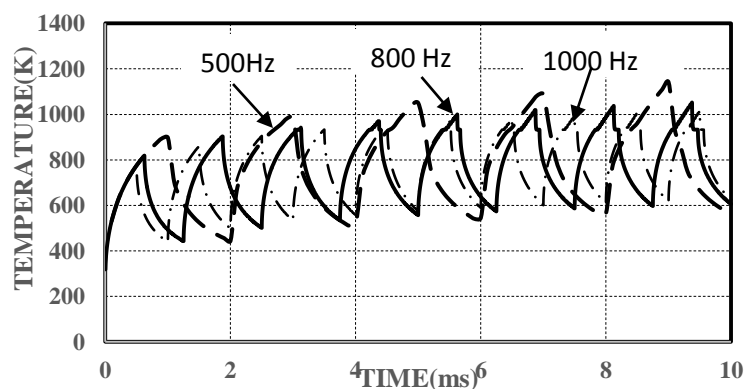


Figure 7. Variation of centre temperature with laser frequency.

With the decrease in laser frequency, the total number of pulses decreases for a particular heating time and heating time per pulse increases that results in attainment of maximum temperature during heating. Simultaneously because of increase in cooling period per pulse, the final temperature attained after total heating period decreases as shown in the Figure 7. With the increase in frequency, number of pulses increases and frequent heating causes increase in final temperature. Therefore, the maximum final temperature is attained for the highest duty cycle.

5. Conclusion

An axisymmetric model was developed and the effects of laser parameters like duty cycle, energy, pulse width and frequency on the performance of melting process were studied for a volumetric Gaussian laser pulse. It was found that with the decrease in duty cycle, the maximum temperature achieved at the centre during heating increases, but the final temperature at the end of total heating period decreases. With increase in laser energy, the maximum temperature achieved during heating increases keeping other parameters constant. Decrease in frequency causes an increase in maximum centre temperature achieved during heating, but the final temperature at the end of total heating period decreases.

In conclusion, the laser machining process can be improved by proper control of different laser parameters and the above derived results from the current numerical analysis can be utilised in practical laser melting process to achieve better results.

References

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