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Spring 2019

Laser Ablation of Aluminum

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Laser Ablation of Aluminum

Erika Nosal
Zachary Rahe
Arthur Pamboukis

The University of Akron
Spring 2019

I. Abstract

The laser ablation of metal carries relevance in a variety of engineering industries. This includes, but is not limited to, processes such as micromachining, or implementation on aircraft weaponry. The latter application is the reasoning for why aluminum is the specific metal in consideration, as it is commonly used for the construction of aircraft components.

The scope of this project was to optimize the energy dispersed through laser ablation on aluminum by mathematical modeling. The transient conduction process in the aluminum was modeled using a 2-dimensional cylindrical coordinate system in both MATLAB and ANSYS/Fluent. These models were adopted to simulate various laser pulse patterns, to accomplish an initial objective of pulse optimization. Specifically, the various pulse patterns were compared, to obtain a pattern that allowed for the aluminum to reach its melting temperature at a specified depth, while consuming the least amount of power from the laser. The duration of, and the time between, the laser pulses were changed to investigate how these parameters affected the efficiency of the energy distribution. Since mass ejection decreases the efficiency of the laser pulse, Ansys/Fluent was used to model the gas dynamics of the ejected material as well. This decrease in efficiency occurs because the created plume absorbs some of the laser's energy, thus reducing the energy being transferred to the target. Investigating this process, known as shielding, is the ultimate objective of the entire project. The optimal pulse pattern determined initially was remodeled, now considering energy absorption in the surrounding air region. Future studies will continue to investigate the process of shielding, to achieve full laser pulse optimization.

Contents

II. Introduction

Laser ablation is the process of removing material using a laser from the surface of a solid. This process is used in many different industries and applications. Some examples are for corrective eye surgeries, rust removal, and the manufacturing of carbon nanotubes. This project is investigating the optimization of laser ablation on aluminum for the use in laser anti-missile and anti-aircraft weapons.

During laser ablation, material is removed as the laser heats the surface turning it into a gas, liquid, or plasma and is ejected from the surface in a plume. As the laser travels through the plume of material, a significant portion of the energy in the laser is absorbed in the plume, making it necessary to use more energy to heat the target region. This absorption of energy by previous plumes is called shielding. The efficiency of laser ablation by multiple laser pulses is decreased by this shielding effect. For each additional pulse more and more energy is absorbed. The longer the duration of the pulse and the more pulses used the greater the decrease in efficiency.

III. Mathematical Modeling - MATLAB

To begin the process of modeling the physical processes occurring during laser ablation, several models were developed. Modeling began with basic numerical methods, and proceeded to increasingly more complex mathematical models.

A. Finite Element Approximation Method

Laser ablation involves the rapid heating of a surface. As such, the very first concept to be considered is that of transient conduction through a surface: in this case, aluminum. Successive laser pulses were simulated by changing the boundary conditions of an aluminum surface between the surface temperature of 5000 K and an adiabatic condition. Thus, the following finite element approximation method was applied for 1 - dimensional transient conduction through a solid surface [2].

(3.1) $$\frac{d^2 T}{dx^2} = \frac{T_{i-1} - 2T_i + T_{i+1}}{\Delta x^2}$$

1. One - Dimensional Finite Element Approximation:

(3.2) $$\frac{T_j^{n+1} - T_j^{n}}{\Delta t} = k\frac{T_{j+1}^{n} - 2T_j^{n} + T_{j-1}^{n}}{\Delta x^2}, \quad \frac{k\Delta t}{\Delta x^2} \leq \frac{1}{2} \text{ (stability criterion)}$$

2. Two - Dimensional Cartesian Finite Element Approximation

(3.3) $\frac{1}{\alpha}\frac{T_{m,n}{}^{p+1}-T_{m,n}{}^{p}}{\Delta t} = \frac{T_{m+1,n}{}^{p}+T_{m-1,n}{}^{p}-2T_{m,n}{}^{p}}{(\Delta x)^2} + \frac{T_{m,n+1}{}^{n}+T_{m,n-1}{}^{p}-2T_{m,n}{}^{p}}{(\Delta y)^2}$

$\frac{\alpha\Delta t}{(\Delta x)^2} \le \frac{1}{4}$ $\frac{\alpha\Delta t}{(\Delta y)^2} \le \frac{1}{4}$ (stability criterion)

3. Two - Dimensional Cylindrical Finite Element Approximation

(3.4) $\frac{1}{\alpha}\frac{T_{r,r}{}^{p+1}-T_{r,x}{}^{p}}{\Delta t} = \frac{1}{r}\frac{T_{r+1,x}{}^{p}-T_{r-1,x}{}^{p}}{2(\Delta r)} + \frac{T_{r+1,x}{}^{n}+T_{r-1,x}{}^{p}-2T_{r,x}{}^{p}}{(\Delta r)^2} + \frac{T_{r,x+1}{}^{n}+T_{r,x-1}{}^{p}-2T_{r,x}{}^{p}}{(\Delta x)^2}$

$\frac{\alpha\Delta t}{(\Delta r)^2} \le \frac{1}{4}$ $\frac{\alpha\Delta t}{(\Delta x)^2} \le \frac{1}{4}$ (stability criterion)

Since these calculations are an iterative process, a MATLAB script was written to perform calculations for each scenario.

B. Simulations: MATLAB and ANSYS Fluent

1. One - Dimensional:

The first mathematical model that was created was a 1-Dimensional transient heat conduction process where the target temperature was an instantaneous 5000K when the laser was on, and an adiabatic condition when the laser was off. Differences in the conductivity value of aluminium based off of temperature were ignored, and all convective and radiative effects were ignored for this approximation. For this model, it is assumed that the rod is long enough to assume that the temperature at the opposite end of the target region is ambient and the initial condition of all the nodes except the target are ambient. To mimic the adiabatic condition at the target region when the laser is off, the following equation is used: $T_j^{n+1} = T_{j+1}^{n}$ This condition makes it so that the temperature of the target region, the top node, is equal to the temperature of the second node at the previous time step. With this model, the stability criterion of $\frac{k\Delta t}{\Delta x^2} \le \frac{1}{2}$ needed to be met. One on/off pulse condition was analyzed using Matlab and produced the following results:

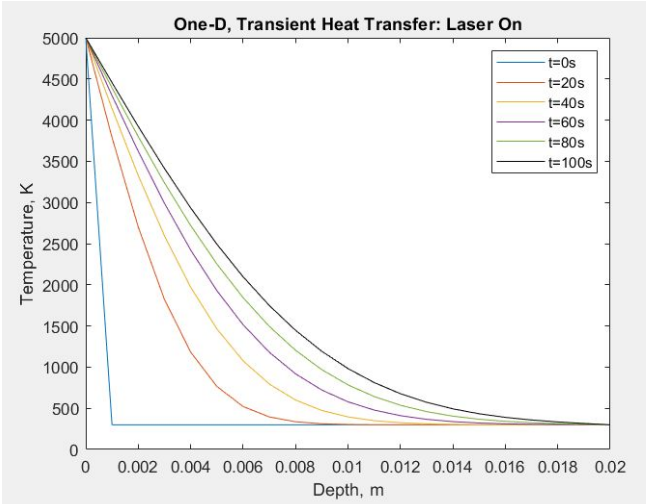


Figure 1.a.

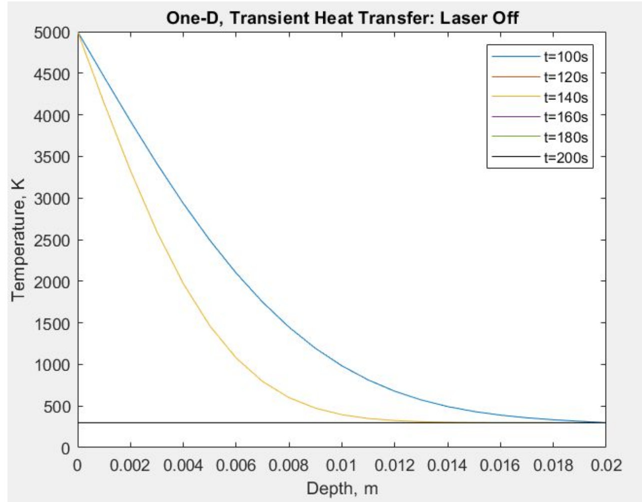


Figure 1.b.

2. Two - Dimensional Cartesian:

Similar assumptions that were made in the 1-Dimensional approximation are also made for the 2-Dimensional scenario; however, with the extra dimension comes additional boundary conditions. The target region is still an instantaneous 5000K when the laser is on, and adiabatic when the laser is off, ie: $T_{m,n}^{P+1} = T_{m,n+1}^{P}$ and the left, right, and bottom bounds of the region are all assumed to be ambient temperature. The initial temperature of all the nodes except for the target region is also ambient. Based off the laser parameters, the target region has a diameter of 1mm, and all other nodes at the top layer of the model are also assumed to be ambient. The target region was set such that it was centered among the top nodes of the model. The finite difference equation shown above (3.3) and the stability conditions stated, were used with these conditions for three pulses, each being on and off for 100 ns, in Matlab.

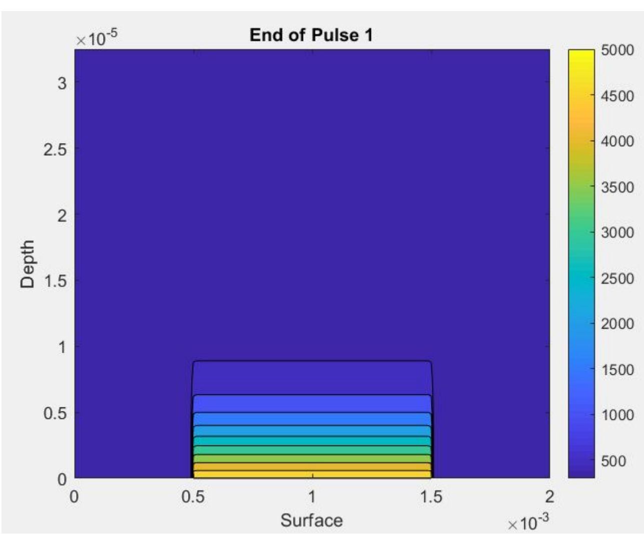


Figure 2.a.

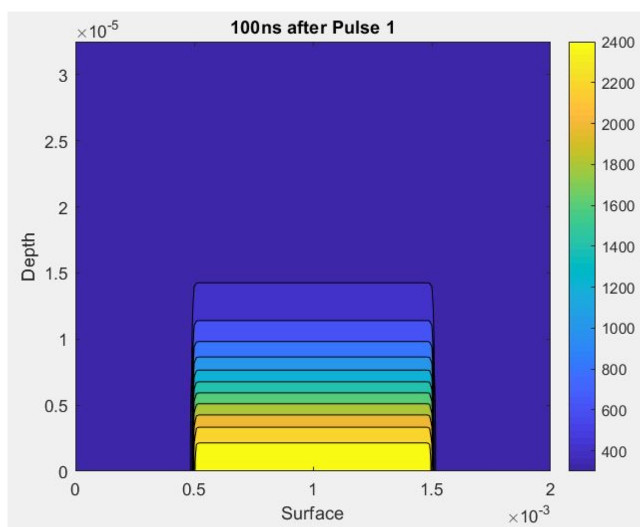


Figure 2.b

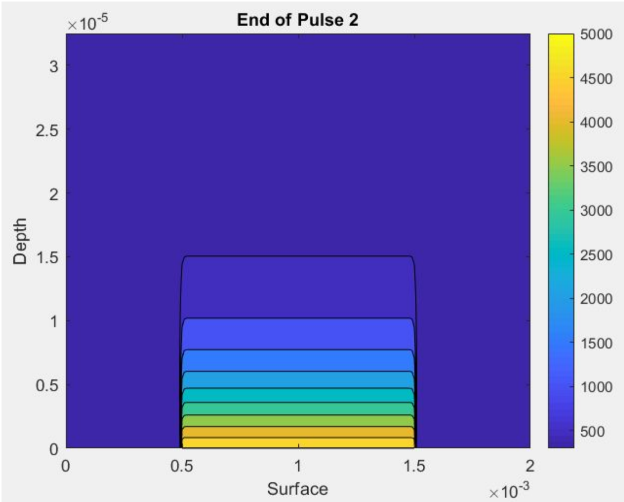


Figure 2.c.

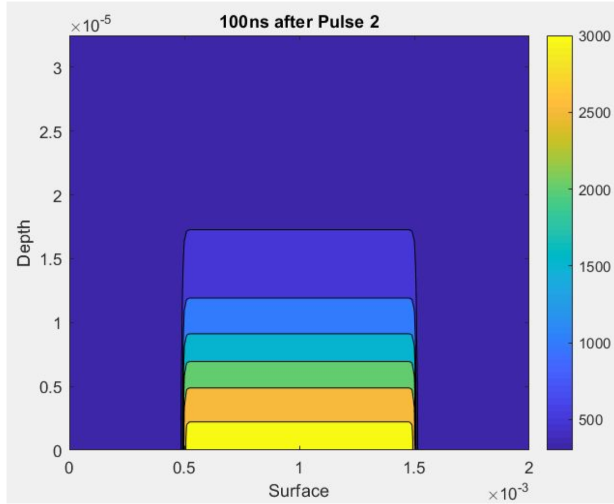


Figure 2.d.

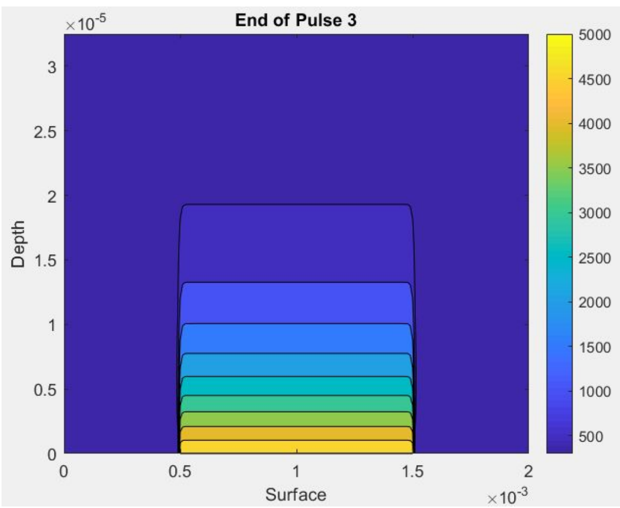


Figure 2.e.

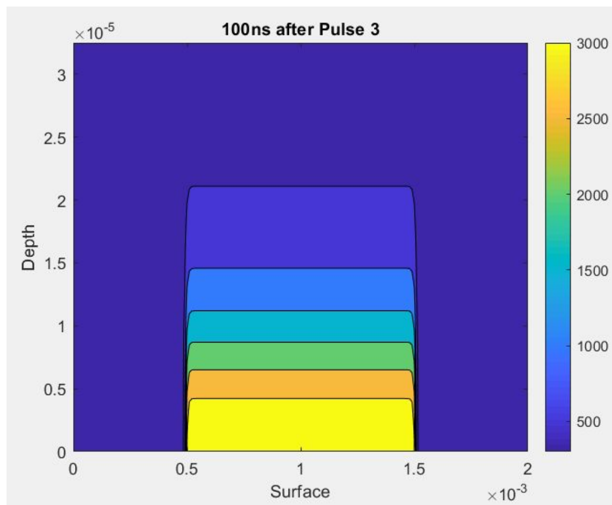


Figure 2.f.

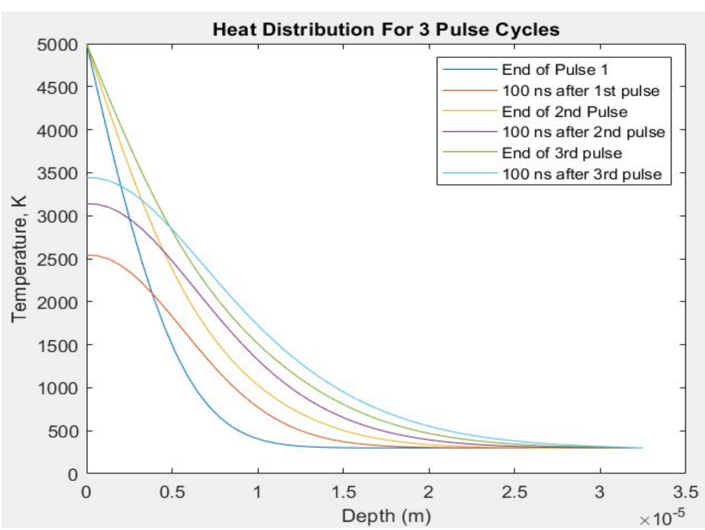


Figure 2.g.

3. Two - Dimensional Cylindrical:

The last mathematical model to be analyzed via finite-difference method was 2-Dimensional axisymmetric cylindrical coordinates. This coordinate system should produce the most accurate results since the target region is circular; and this system was used in previous research done by Dr. Povitsky, so this will allow the results from both to be compared. This model still assumes an instantaneous target temperature of 5000K when the laser pulse is on and an adiabatic condition of $T_{r,x}{}^{P+1} = T_{r,x+1}{}^{P}$ when it is off. The target region is the top layer spanning from the left most node to the radius of the laser. The right and bottom bounds are assumed to be ambient temperature along with all other temperatures at the top layer outside the target region. The initial state of all the nodes is also ambient except for the target region. At the axis, the left bounds, it is assumed that the temperature gradient is zero: $T_{r+1,x}{}^{P} = T_{r,x}{}^{P}$. Since this model will be used to compare results, the Matlab script was written so it could analyze the results for any inputted number of pulses given that the time of the pulse is equal to the time that is off. Using these conditions with the Matlab script attached in Appendix C for three pulses produced the following results:

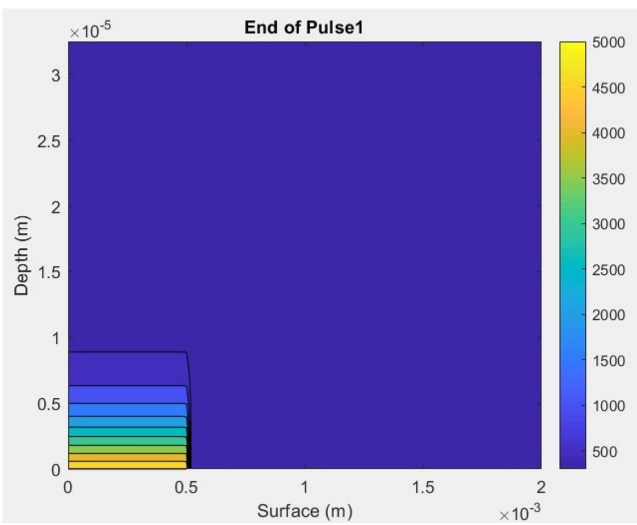


Figure 3.a.

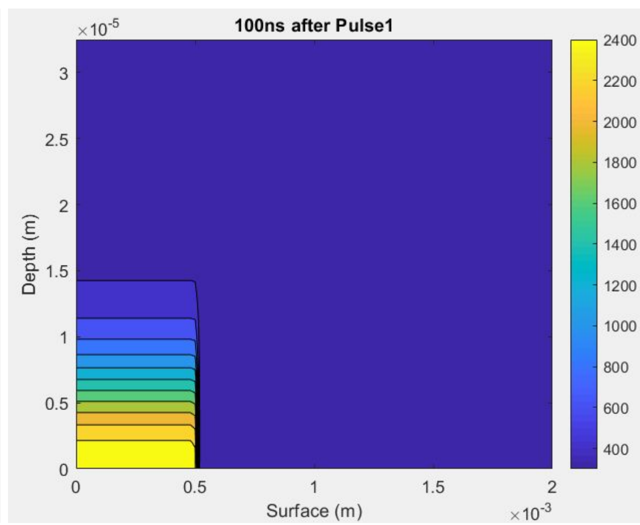


Figure 3.b.

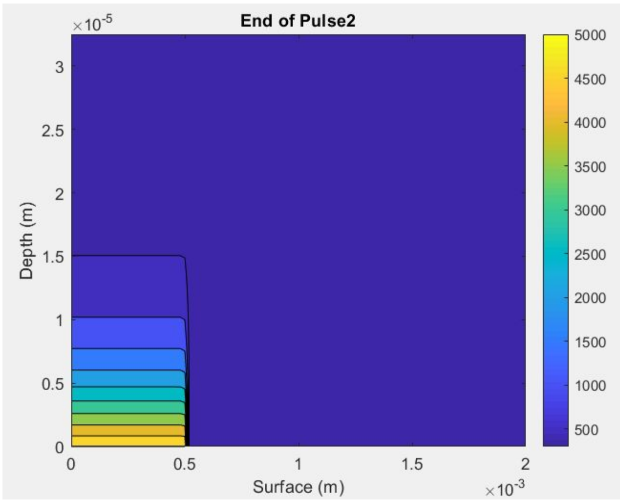


Figure 3.c.

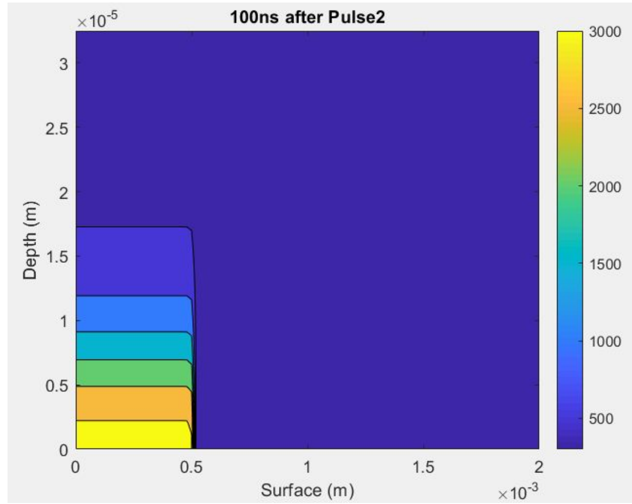


Figure 3.d.

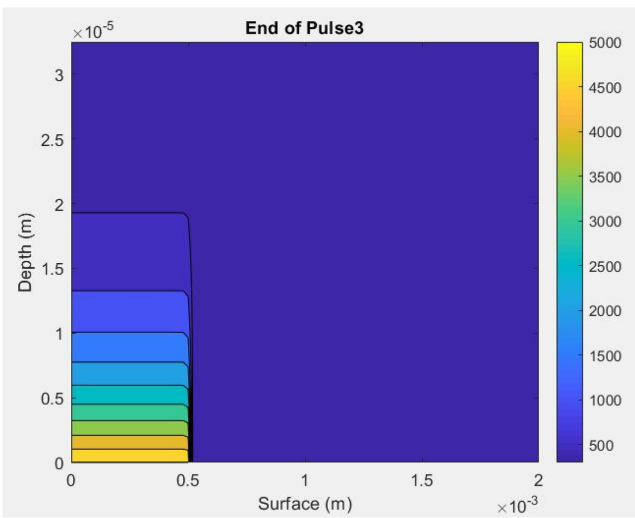


Figure 3.e.

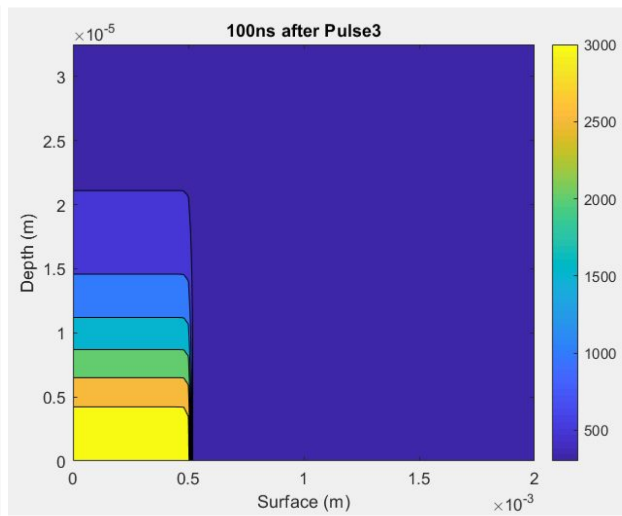


Figure 3.f.

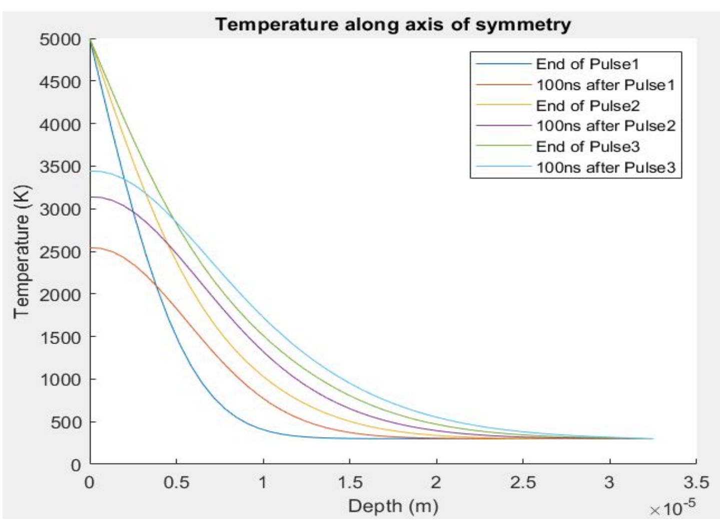
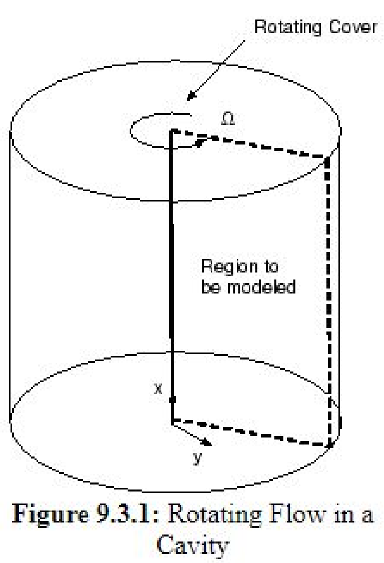


Figure 3.g.

Geometry and Boundary Conditions:

The following images provide further information regarding the geometry of the laser pulse. As evident in Figure 4, the circular target region allows for the application of a 2-D axisymmetric model, since heat propagates downward in a cylindrical fashion. Figures 5 and 6 illustrate the concept of axisymmetric geometry.

Figure 4.a. Basic illustration of the target area, pulse on (left), and pulse off (right).



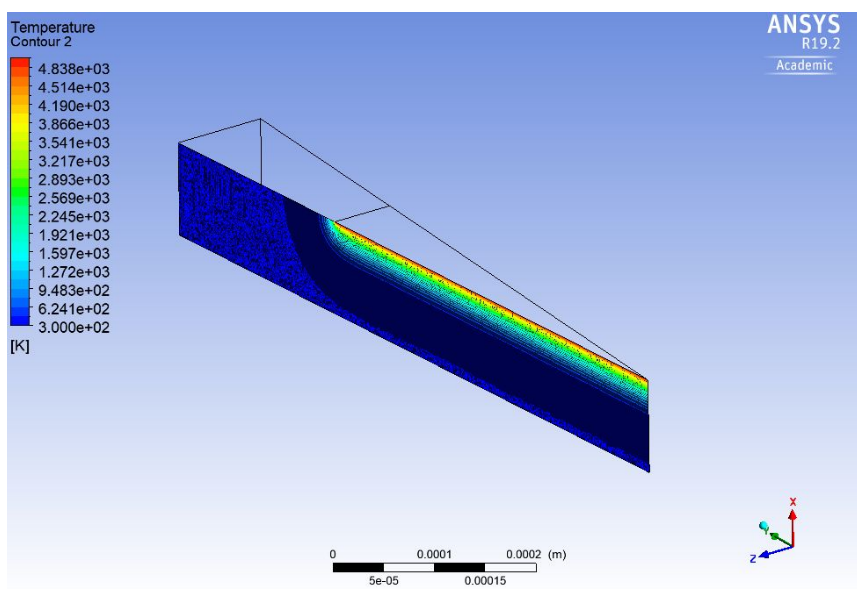


Figure 5. 2D Axisymmetric in ANSYS 19.2 [4]

Figure 6. Temperature distribution immediately after the 10th pulse, Case A100.

IV. Simulations - ANSYS Fluent

A. Temperature Distribution of The Heated Aluminum

Modeling the behavior of aluminum during a laser ablation process involves the consideration of many physical processes, including, but not limited to: transient conduction, convection, radiation, chemical processes, and fluid mechanics. Modeling began by starting with a 1-Dimensional numerical analysis in MATLAB. Next, a 2-Dimensional model was constructed in ANSYS Fluent using cartesian coordinates, followed by a 2-Dimensional axisymmetric model for further accuracy. Complete results and figures are present within the Appendix. Initial models were constructed for a pulse pattern of 100 ns on, 100 ns off, known as Case 100A in Section IV - 3. The figure below, generated in MATLAB, depicts the rate at which temperature would be expected to decrease in relation to material depth. This observation was then validated in ANSYS Fluent.

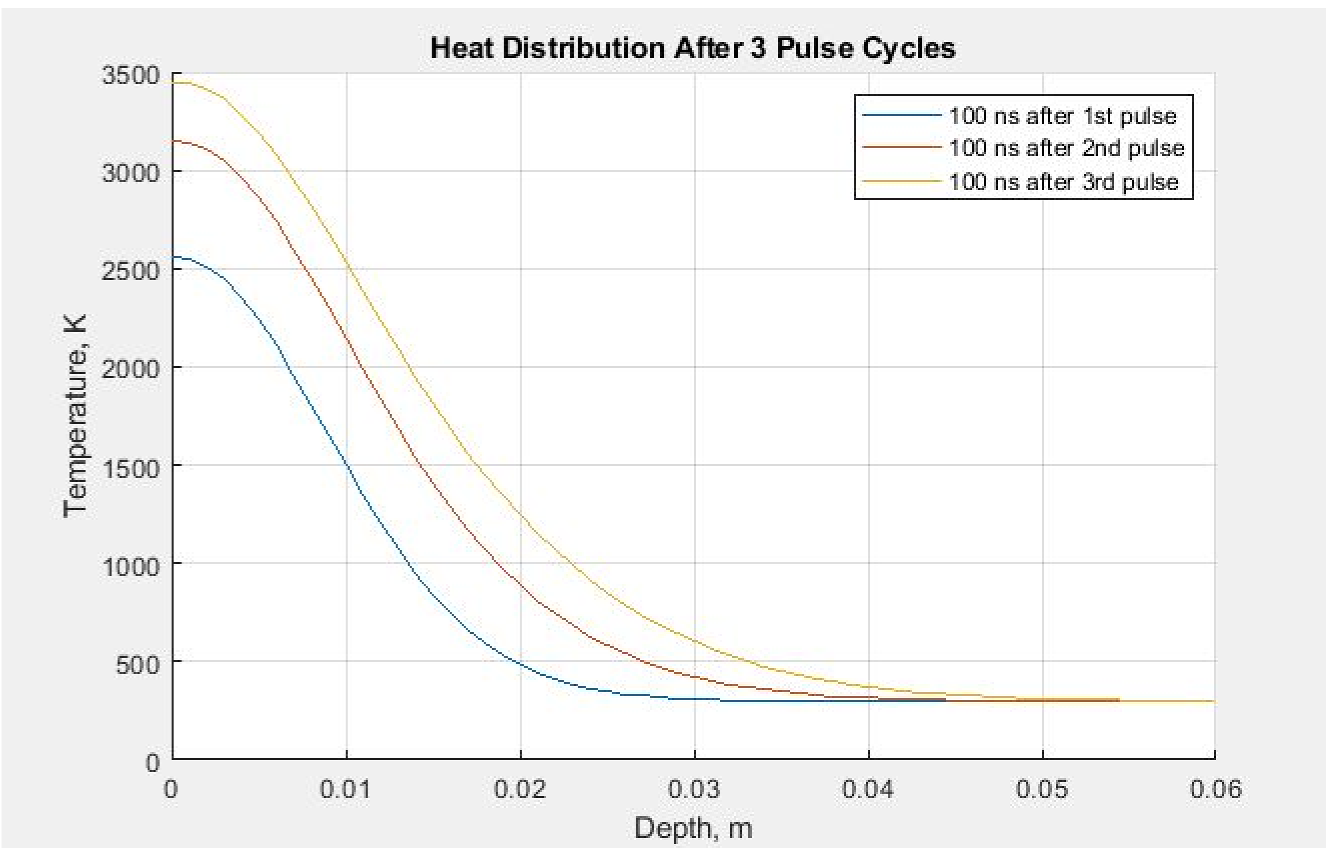


Figure 7. One - Dimensional temperature gradient through an aluminum solid at specified points in time.

These initial models for heat conduction are rather simple. Realistically, there are many factors that must be considered, such as the optical properties of aluminum at high temperatures, solidification and melting, as well as ionization, to name a few. However, this model is intended to hopefully act as the framework for more complex models, and provide some insight into the process of laser ablation.

2. Two - Dimensional Model

ANSYS Fluent

Initial Conditions:

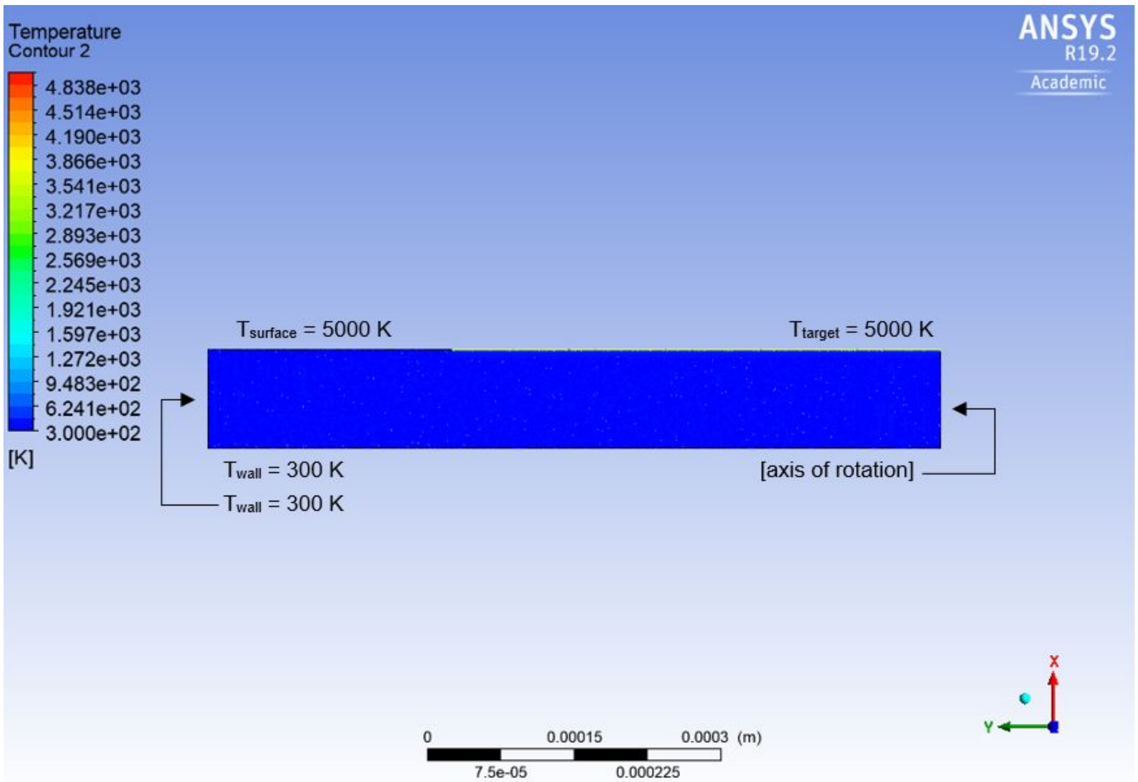


Figure 8. Initial Conditions for Case A100, where t = 0 ns. (timestep: n = 1).

Boundary Conditions: Pulse OFF

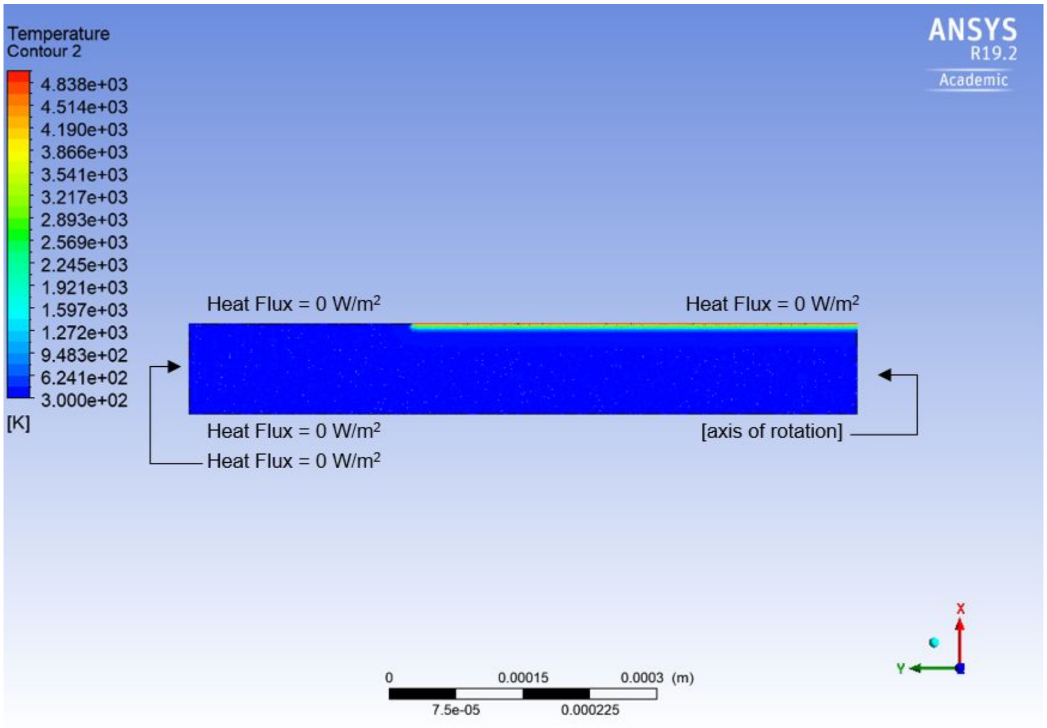


Figure 9. Boundary Conditions for Case A100 immediately after pulse 1, where t = 100 ns. (timestep: n = 101)

Boundary Conditions: Pulse ON

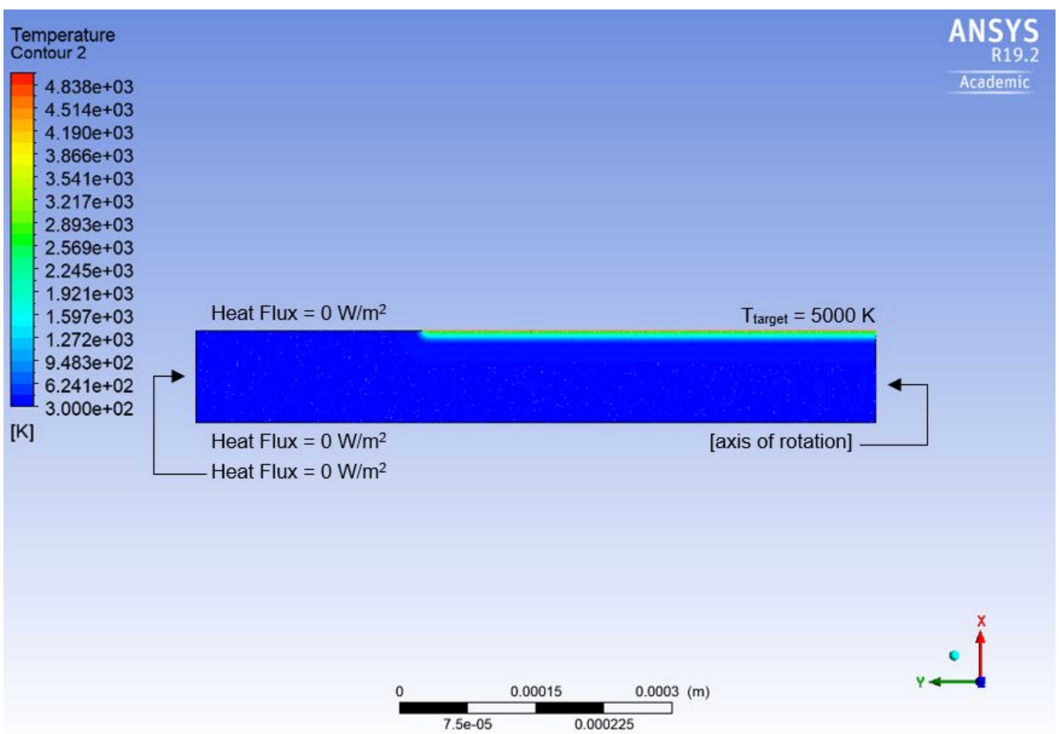


Figure 10. Boundary Conditions for Case A100 immediately beginning pulse 2, where t = 200 ns. (timestep: n = 201)

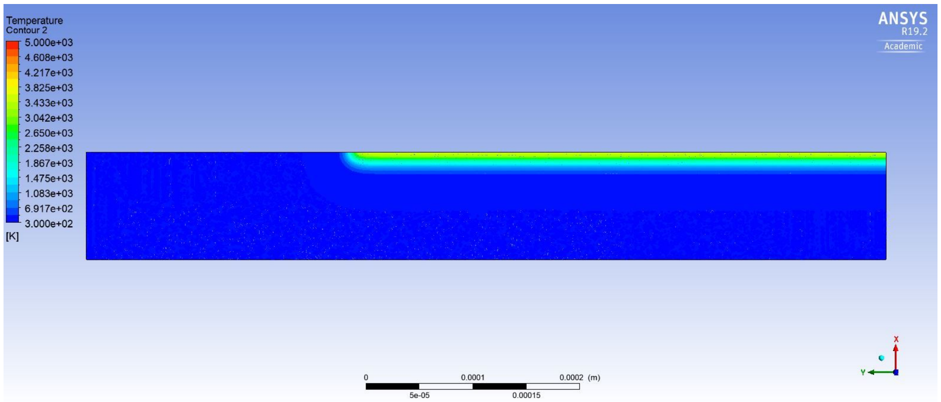


Figure 11. Fig. Temperature Distribution 100 ns after pulse 3, Case A100.

Temperature distributions were verified in MATLAB, present in the Appendices.

3. Pulse Optimization

As with many engineering endeavors, the ultimate purpose of this investigation into the ablation of aluminum is to provide conclusions that may be useful for industrial purposes. Thus, an investigation into pulse pattern optimization was conducted. The purpose of this investigation was to determine whether or not certain pulse durations and patterns allowed for the aluminum to reach its melting point using the least amount of power. Power efficiency is a design constraint prevalent through a multitude of engineering subdisciplines, and thus, its consideration was relevant. Twelve different pulse patterns were simulated in ANSYS Fluent. For investigative purposes, temperatures were recorded at two arbitrary points below the target surface: 10 μm, and 20 μm.

Table 1. Performance Parameters of a Variety of Pulse Patterns

Various Pulse Patterns				
Surface Condition:	$T_{surface} = 5000\ K$	$q'' = 0\ W/m^2$		
Case No.	$\tau\ (nanoseconds)$	$\tau\ (nanoseconds)$	No. of Pulses	$\tau_{final}(nanoseconds)$
A100	100	100	12	2400
A200	200	200	6	2400
A400	400	200	3	2400
A600	600	600	2	2400
B100	100	100	9	1800
B200	200	100	6	1800
B400	400	100	4	2000

These pulse patterns were primarily evaluated in ANSYS Fluent. The objective of this procedure was to examine whether or not laser pulses could be optimized to reach an arbitrary target depth using the least amount of energy.

Temperature as a Function of Time

The following figures were generated to observe how quickly aluminum would be heated to its melting temperature of 933 K, under different conditions.

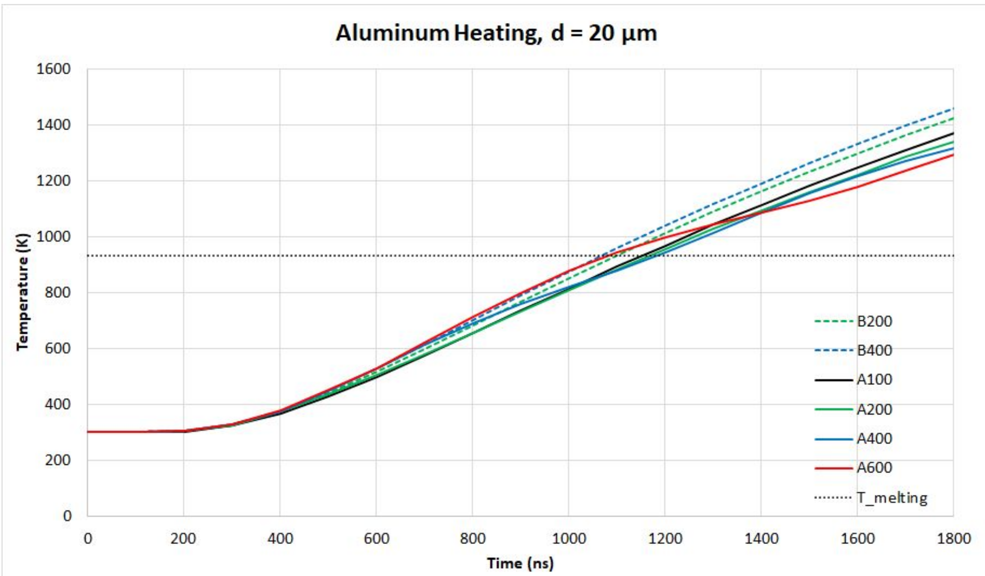


Figure 12.a. Temperature of the aluminum at an arbitrary depth of 20 microns below the aluminum surface.

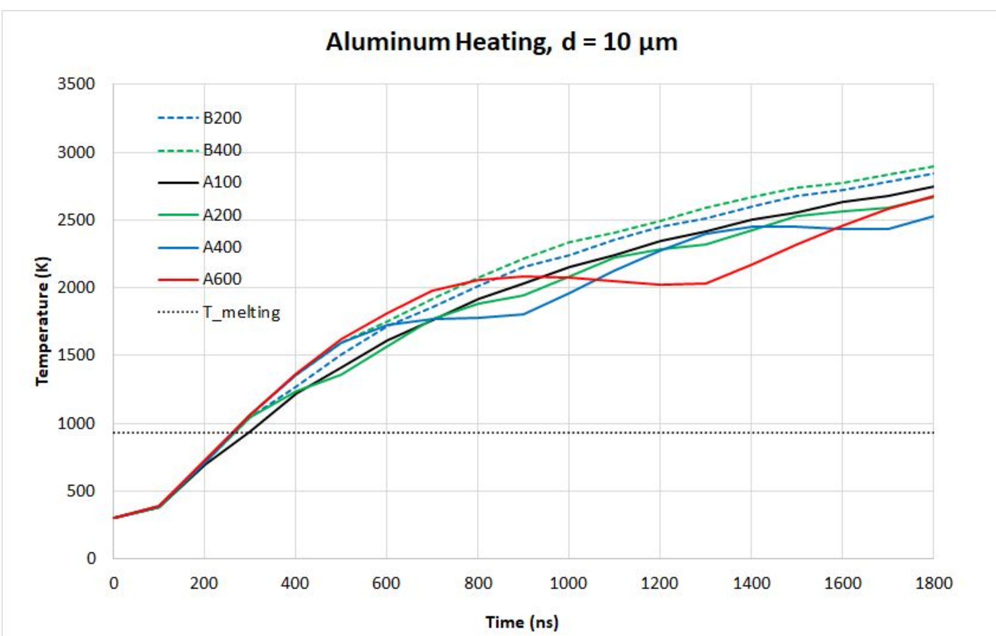


Figure 12.b. Temperature of the aluminum at an arbitrary depth of 10 microns below the aluminum surface.

Temperature as a Function of Input Power

Heat propagation through the aluminum appears to vary little with variations in pulse patterns, when time is the primary factor of interest. Thus, another, and perhaps more practical metric shall be investigated: power. The power required to heat the aluminum to its melting temperature for a variety of arbitrary depths was plotted for the set of pulse patterns listed in Table 1:

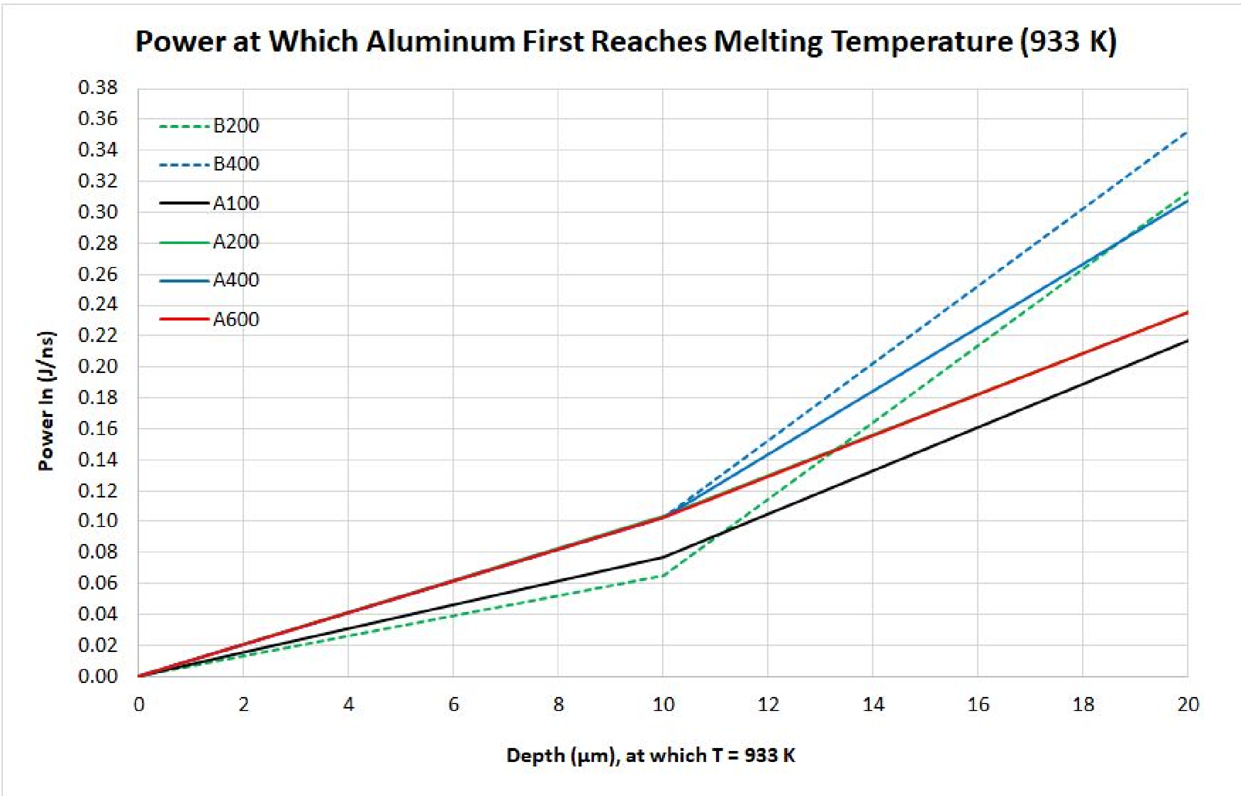


Figure 13. Power required to reach the melting temperature of Aluminum at the two specified arbitrary depths. For this model, a sample laser fluence of 5 J/cm² was used, with 100 ns being the default time period for power units.

Table 2. Relevant Parameters Used:

Pulse Radius (m)	Pulse Area (m^2)	Fluence (J/m^2)	Energy (J)
0.0005	7.8539E-07	50000	0.0392

It is important to note that the data acquired for pulse optimization occurs over a relatively short length of time. Ideally, further simulations can provide more insight into the true behavior of aluminum as it is heated. The miniscule time length was chosen to hopefully maintain accuracy. Longer simulations will require the following considerations, thus complicating the model:

- The ejection of mass, and subsequent formation of craters
- Energy scattering and absorption due to shielding
- Additional thermodynamic processes

B. Gas Dynamics of the Surrounding Region

As the laser heats the aluminum above its melting point the liquid and gaseous material is ejected at high speed from the surface. The ejected material absorbs some of the energy from next pulse reducing the amount of energy that hits the target. The amount of laser light that passes through the plume is modeled with Bouguer-Lambert-Beer law as follows:

(4.1) $I/I_0 = e^{-\int_0^L K_{ext}(\lambda)dx}$

λ is the wavelength of the laser beam, L is the path length that the laser travels through the plume, K_{ext} is the extinction coefficient of the plume. I/I_0 represents the percentage of laser energy that is transmitted through the plume.

K_{ext} is calculated as follows:

(4.2) $K_{ext}(\lambda) = \frac{\pi}{4} C_n Q_{ext}(\lambda) D_p^2$

Where C_n is the number density of particles, D_p is diameter of the particles assuming all liquid droplets have the same size, and Q_{ext} is the extinction efficiency.[4]

Using Mie Theory, Q_{ext} can be solved by

(4.3) $Q_{ext}(\lambda) = 2 - \frac{4}{\alpha} sin(\alpha) + \frac{4}{\alpha^2}(1 - cos(\alpha))$

$\alpha = \frac{2\pi D_p}{\lambda} |m - 1|$

Where m is the refractive index of aluminum which is 5/3.

In order to get the path length L the plume needs to be modeled using Navier-Stokes equations. This was done by using Ansys/Fluent

In order to model the Navier-Stokes solution the ejection velocity of the molten material of the plume is needed. This is solved for using the equations for mass flow rate as follows

(4.4) $mdot = \rho V A$

(4.5) $mdot = m/t$

Where mdot is the mass flow rate, ρ is the density, V is the velocity, A is the area of the target and t is the duration of the pulse

The ejected mass was solved by taking the depth at which the laser heated the aluminum to above its melting point of 933 K. As the radius of the target is .5mm, the volume of the ablated mass is calculated and multiplied by the density of solid aluminum to get the ablated mass. The mass was divided by the duration of the pulse to get a mass flow rate of 0.1272 kg/s. This mass flow rate was divided by the area of the target and the density of the gas-liquid mixture that is ejected to get an ejection velocity of 192.86 m/s. (see Appendix B for calculations)

The pressure of the ejected material is assumed to be the saturated vapor pressure of aluminum at the target temperature of 5000K. The equation to calculate the pressure is:

(4.6) $log(\frac{P_s}{P_a}) = A + B/T + ClogT$

Where A is 9.445, B is -16380 and C is 1.0. [3] P_a is atomostspere ic pressure of 1.01 bar, T is the temperature which was taken as the surface temperature of 5000 K, and P_s is the saturated pressure. The pressure of the ejected material is 100 bar.

Using the properties of liquid aluminum and the boundary conditions for the target, the injection velocity and saturated pressure the plume was modeled. The rect of the aluminum surface was set as a wall and all other boundaries as outlets. The injection was run for 100 ns to simulate the pulse length and then was turned off for 100 ns to simulate the length between pulses. The model of the plume is shown in figure 14.

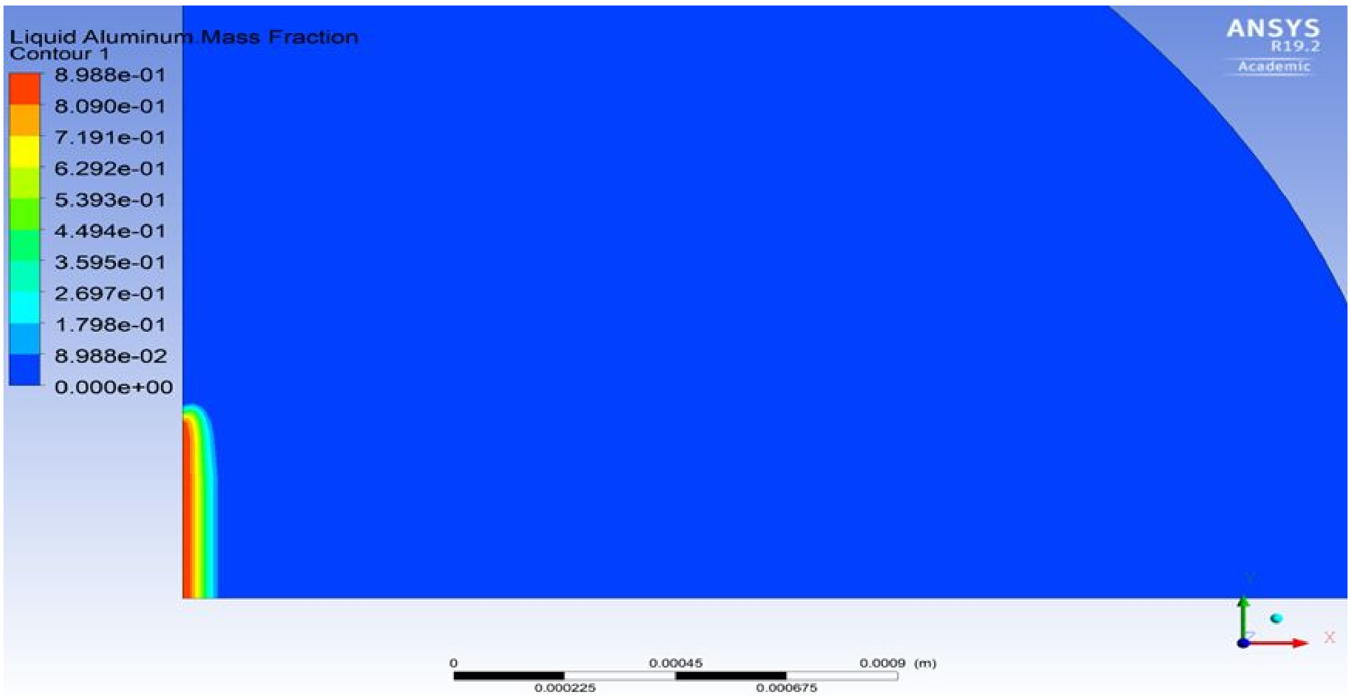


Figure 14. Formation of plume after 100 ns pulse and 100 ns break

To see the shape the plume takes over time the pulse was run for 100 ns and then allowed to run with not material being injected until the total time elapsed is 40 microseconds. The shape of the plume is shown in figure 15.

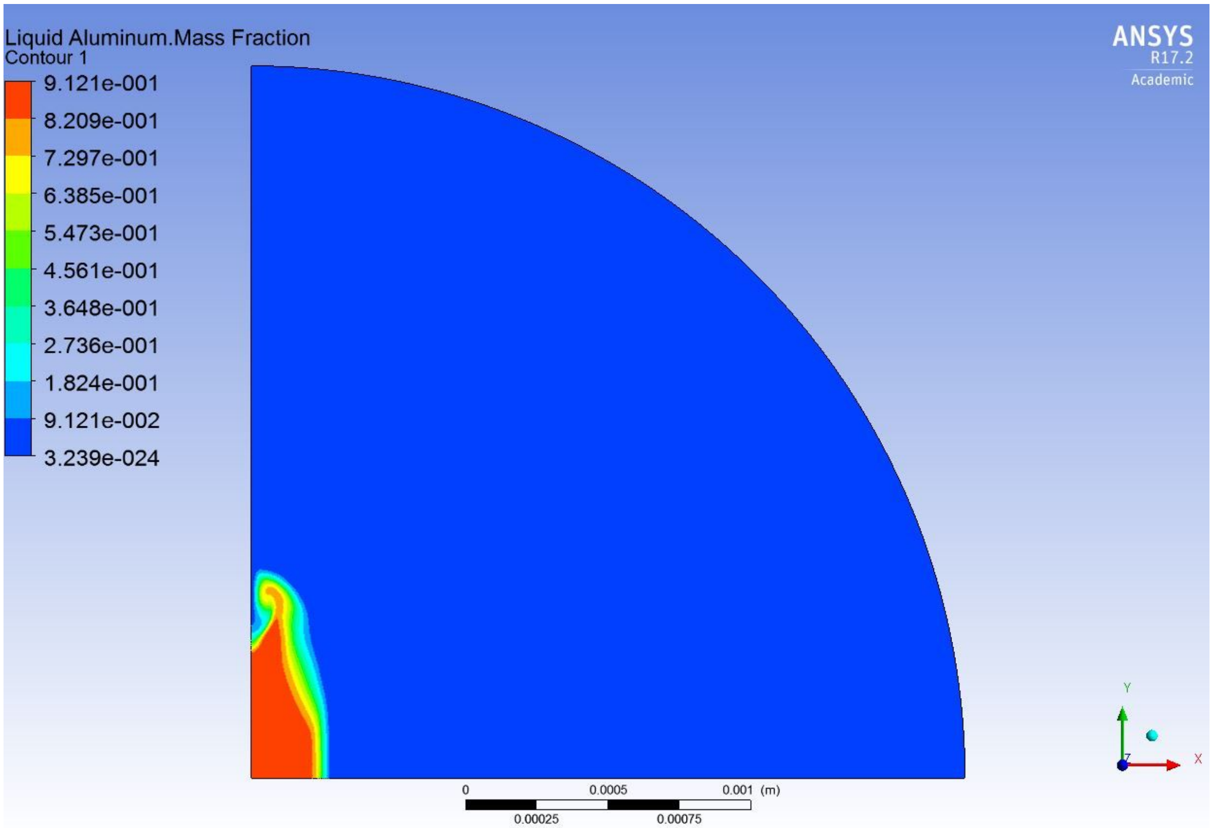


Figure 15. Formation of plume after 40 microseconds

From the simulation of the 100 ns pulse the shape is very similar to a column plume and this approximation was used to calculate the optical length L to use in (5). The length was calculated by multiply the injection velocity by the duration of the pulse to get a length of 1.92*10^-5 m. This length can then be used in (5) to calculate the percentage of the energy from the laser that reaches the target. Using the numbers given in [4] for K_{ext} the intensity of energy transmitted through the plume after 1 pulse cycle is 95%. Thus, there is a reduction in energy transmitted to the material.

V. Accounting for Shielding

The current model for the laser ablation process is rather simplified in its current state. Thus, to examine the effects of shielding, rough approximations will be used. To simulate the reduced energy interacting with the target area, the cases used to model transient conduction in Section IV - 3 were used, with modified boundary conditions.

Plume models presented in Section IV - B require further development. Thus, the effects of shielding were primarily studied within the transient conduction models generated in MATLAB and ANSYS Fluent. Exact percentages of energy decrease require further investigation. As a result, approximate values were implemented, simply to observe how a general decrease in energy to the target affects heat transfer. For approximations, a coefficient of 0.5 was used to calculate the energy being transferred to the target region. This value differs than the 95% stated previously but should better represent the shielding since the previous was a rough estimate. The initial specific energy transfer to the target, knowing that it heats to approximately 5000K, was approximated using the following equation:

(5.1) $q_i = C_p * (T_{Target} - T_{amb})$

The proceeding specific energy transfer was calculated using the following approximation:

(5.2) $q = {C_{shielding}}^{Np-1} * q_i$

Where Np denotes the number of iterations such that at Np=1 is the first pulse. For pulses after the initial one, the previous equation was rewritten to calculate the new target Temperature.

(5.3) $T_{Target} = q/C_p + T^{p-1}$

Where T^{p-1} represents the temperature at that region at the previous time step. These conditions were added to the two-Dimensional Cylindrical Matlab script described in section III B: Simulations: MATLAB and ANSYS Fluent. Below are the Temperature v. Depth graphs produced by the Cylindrical calculations with and without shielding.

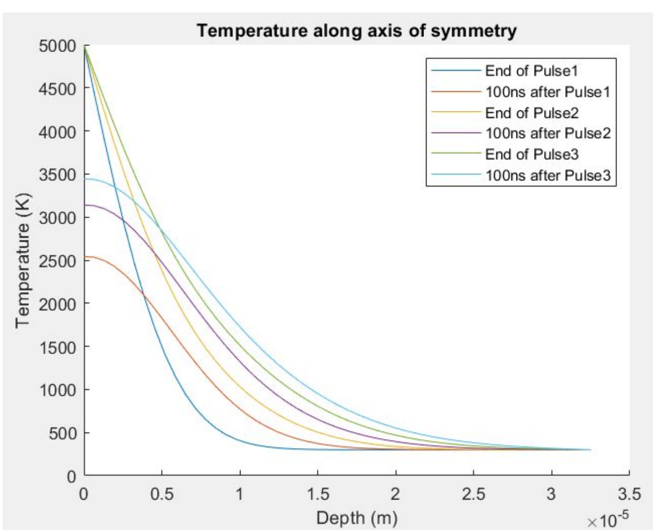


Figure 16.a. Temperature Distribution without shielding

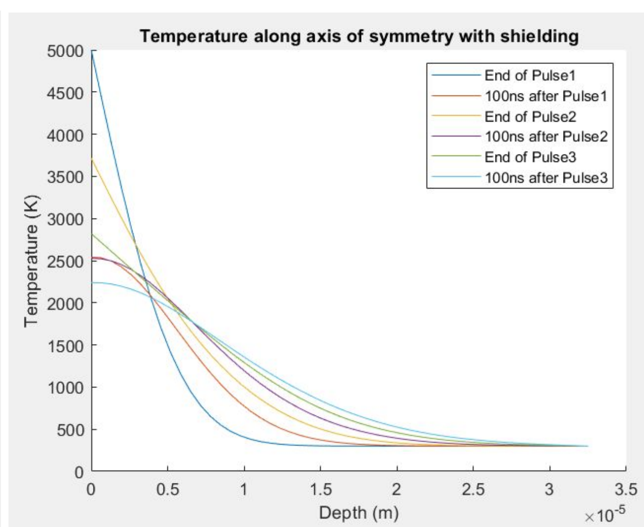


Figure 16.b. Temperature Distribution with shielding

As shown, the target temperature after each pulse drops and reduces the temperature gradient throughout the model. This type of reaction makes physical sense because as more energy is being absorbed by the plume, less energy can go to the target region; so even though more research needs to be done to better account for shielding, this model represents the temperature distribution than the one without. Boundary conditions obtained in MATLAB were implemented in ANSYS Fluent. The following figure summarizes the temperature distribution data obtained in MATLAB:

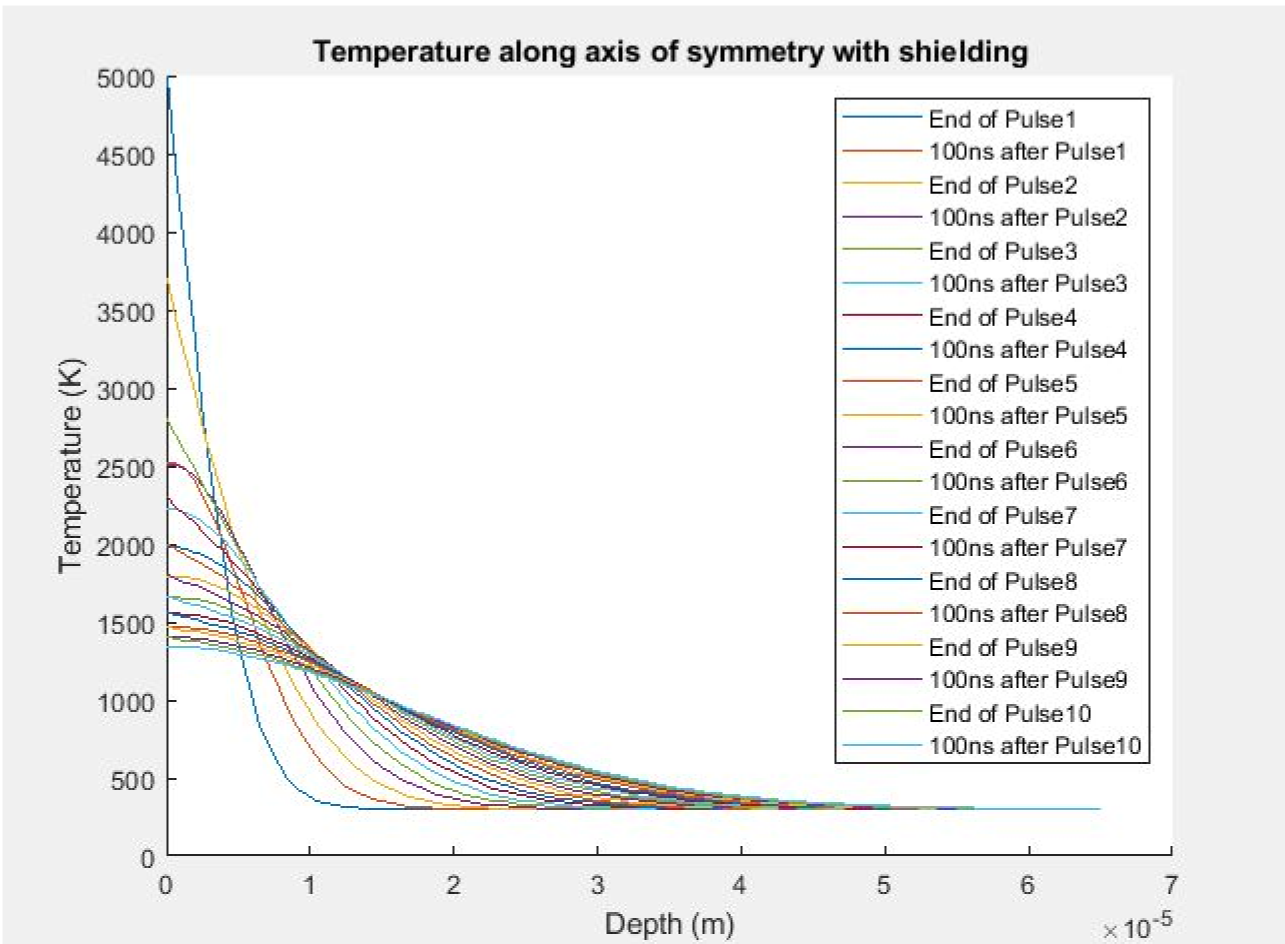


Figure 17. Temperature distribution of Case A100, with shielding considered.

VI. Conclusions

From the examination of of shielding from the plume absorbing laser energy, a shorter pulse is more efficient as it allows less time for the formation of the plume. As the plume is smaller, the optical path length is shorter, so the decreasing the amount of energy absorbed by the plume. In addition, shorter pulses seem favorable with regard to power efficiency and heat propagation. Figure 11 exhibits this, with Case A100 displaying the lowest required power to heat aluminum to its melting temperature.

References

[1] Bergman,T.L., Lavine, A.S., Incropera, F.P., & Dewitt, D.P. (2011). *Introduction to Heat Transfer: Sixth Edition.* Hoboken, NJ: John Wiley & Sons, Inc.

[2] Chapra, S.C. (2012). *Applied Numerical Methods with MATLAB for Engineers and Scientists: Third Edition.* New York, NY: McGraw-Hill.

[3] *Marla et al, Models for predicting temperature dependence of material properties of aluminum, J. Phys. D: Appl. Phys. 47 (2014) 105306*

[4] *Povitsky, Alex. Laser ablation and plume shielding effect,(2018)*

Appendix A

Temperature Distribution Data Acquired in ANSYS Fluent:

Case 1: [100 ns on, 100 ns off]		[100 ns]		[100 ns]		[100 ns]	300 ns total																		
Pulse #		1		2		3		4		5		6		7		8		9		10		11		12	
target condition (K)		5000	adb	5000	adb	5000	adb	5000	adb	5000	adb	5000	adb	5000	adb	5000	adb	5000	adb	5000	adb	5000	adb	5000	adb
time (ns)	0	100	200	300	400	500	600	700	800	900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000	2100	2200	2300	2400
x2 (m)		0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008
x1 (m)		0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009
y (m)		0.000375059	0.000375059	0.000375059	0.000375059	0.000375059	0.000375059	0.000375059	0.000375059	0.000375092	0.000375092	0.000375024	0.000375024	0.000375002	0.000375002	0.000375002	0.000375002	0.000375002	0.000375002	0.000375077	0.000375077	0.000375077	0.000375077	0.000375077	0.000375077
z (m)	300	2.45757E-05	2.45757E-05	2.45757E-05	2.45757E-05	2.45757E-05	2.45757E-05	2.45757E-05	2.45757E-05	2.45783E-05	2.45783E-05	2.45764E-05	2.45764E-05	2.45737E-05	2.45737E-05	2.45737E-05	2.45737E-05	2.45737E-05	2.45737E-05	2.45919E-05	2.45919E-05	2.45919E-05	2.45919E-05	2.45919E-05	2.45919E-05
[K] d2 = 20 (µm)	300	300.025	303.671	325.243	367.609	427.048	497.321	574.3	654.078	734.881	814.743	893.196	969.214	1042.91	1113.72	1181.99	1247.35	1310.24	1370.39	1428.24	1483.58	1536.86	1587.86	1637.01	1684.12
[K] d1 = 10 (µm)	300	382.007	693.19	944.958	1217.26	1411.4	1616.27	1760.4	1918.35	2028.31	2154.36	2240.91	2344.58	2414.35	2501.68	2559.12	2634.14	2682.25	2747.74	2788.54	2846.45	2881.57	2933.36	2963.82	3010.58
Case A200: [200 ns on, 200 ns off]																									
Pulse #			1				2				3				4				5				6		
target condition (K)			5000	adb			5000	adb			5000	adb			5000	adb			5000	adb			5000	adb	
time (ns)	0	100	200	300	400	500	600	700	800	900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000	2100	2200	2300	2400
x2 (m)		0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008
x1 (m)		0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009
y (m)		0.000375085	0.000375085	0.000375085	0.000375085	0.000375085	0.000375085	0.000375085	0.000375085	0.000375085	0.000375085	0.000375085	0.000375085	0.000375085	0.000375085	0.000375085	0.000375085	0.000375085	0.000375085	0.000375085	0.000375085	0.000375055	0.000375055	0.000375055	0.000375055
z (m)		2.45993E-05	2.45993E-05	2.45993E-05	2.45993E-05	2.45993E-05	2.45993E-05	2.45993E-05	2.45993E-05	2.45993E-05	2.45993E-05	2.45993E-05	2.45993E-05	2.45993E-05	2.45993E-05	2.45993E-05	2.45993E-05	2.45993E-05	2.45993E-05	2.45993E-05	2.45993E-05	2.45832E-05	2.45832E-05	2.45832E-05	2.45832E-05
[K] d2 = 20 (µm)	300	300.034	303.88	326.71	374.91	438.259	505.396	577.165	655.346	734.499	809.087	881.993	956.127	1028.29	1094.85	1158.85	1223.13	1285.22	1342.2	1396.87	1451.81	1504.86	1553.47	1600.18	1647.33
[K] d1 = 10 (µm)	300	383.562	715.606	1049.08	1237.64	1362.15	1573.45	1774.24	1879.66	1946.42	2085.18	2221.38	2285.82	2323.07	2424.04	2525.75	2568.23	2589.34	2668.07	2748.96	2778.38	2789.88	2854.23	2921.38	2942.4
Case A400: [400 ns on, 400 ns off]																									
Pulse #					1								2								3				
target condition (K)					5000	adb							5000	adb							5000	adb			
time (ns)	0	100	200	300	400	500	600	700	800	900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000	2100	2200	2300	2400
x2 (m)		0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008
x1 (m)		0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009
y (m)		0.000375028	0.000375028	0.000375028	0.000375028	0.000375028	0.000375028	0.000375028	0.000375028	0.000375028	0.000375028	0.000375028	0.000375028	0.000375028	0.000375028	0.000375028	0.000375028	0.000375028	0.000375028	0.000375028	0.000375028	0.000375028	0.000375028	0.000375028	0.000375028
z (m)		2.45715E-05	2.45715E-05	2.45715E-05	2.45715E-05	2.45715E-05	2.45715E-05	2.45715E-05	2.45715E-05	2.45715E-05	2.45715E-05	2.45715E-05	2.45715E-05	2.45715E-05	2.45715E-05	2.45715E-05	2.45715E-05	2.45715E-05	2.45715E-05	2.45715E-05	2.45715E-05	2.45715E-05	2.45715E-05	2.45715E-05	2.45715E-05
[K] d2 = 20 (µm)	300	300.056	304.289	327.53	376.605	446.441	528.622	613.115	691.45	759.712	819.347	879.03	944.267	1014.49	1086.83	1156.53	1219.07	1272.56	1318.61	1364.06	1413.32	1466.18	1520.61	1572.96	1619.66
[K] d1 = 10 (µm)	300	386.6	715.583	1064.59	1363.2	1597.84	1722.3	1768.33	1775.33	1807.43	1959.53	2127.9	2276.96	2395.64	2447.59	2450.77	2430.25	2432.06	2527.35	2638.37	2737.84	2816.33	2843.43	2832.69	2803.85
Case A600: [600 ns on, 600 ns off]																									
							600 ns total																		
Pulse #							1												2						
target condition (K)							5000	adb											5000	adb					
time (ns)	0	102	204	300	400	504	600	702	800	900	1002	1104	1200	1302	1404	1500	1602	1704	1800	1902	2004	2100	2202	2304	2400
x2 (m)		0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008
x1 (m)		0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009
y (m)		0.000375055	0.000375055	0.000375055	0.000375055	0.000375055	0.000375055	0.000375055	0.000375055	0.000375055	0.000375055	0.000375055	0.000375055	0.000375055	0.000375055	0.000375055	0.000375055	0.000375055	0.000375055	0.000375055	0.000375055	0.000375055	0.000375055	0.000375055	0.000375055
z (m)		2.45828E-05	2.45828E-05	2.45828E-05	2.45828E-05	2.45828E-05	2.45828E-05	2.45828E-05	2.45828E-05	2.45828E-05	2.45828E-05	2.45828E-05	2.45828E-05	2.45828E-05	2.45828E-05	2.45828E-05	2.45828E-05	2.45828E-05	2.45828E-05	2.45828E-05	2.45828E-05	2.45828E-05	2.45828E-05	2.45828E-05	2.45828E-05
[K] d2 = 20 (µm)	300	300.095	305.184	328.329	378.649	450.189	529.722	620.949	714.007	797.686	877.332	945.329	998.842	1045.78	1086.46	1127.53	1178.99	1237.41	1296.15	1360.17	1423.67	1479.84	1532.61	1577.01	1611.33
[K] d1 = 10 (µm)	300	394.376	729.956	1062.94	1366.56	1618	1815.99	1981.9	2062.49	2082.18	2073.31	2049.52	2020.66	2034.95	2174.94	2322.76	2461.53	2579.49	2674.73	2754.02	2780.58	2770.26	2741.14	2703.5	2664.85
	0	100	200	300	400	500	600	700	800	900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000	2100	2200	2300	2400
	933	933	933	933	933	933	933	933	933	933	933	933	933	933	933	933	933	933	933	933	933	933	933	933	933

Case B100: [100 ns on, 100 ns off]																				
Pulse #	1		2		3		4		5		6		7		8		9			
target condition (K	5000	adb	5000	adb	5000	adb	5000	adb	5000	adb	5000	adb	5000	adb	5000	adb	5000	adb		
time (ns)	100	200	300	400	500	600	700	800	900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000
x2 (m)	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008		
x1 (m)	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009		
y (m)	0.00037506	0.00037506	0.00037506	0.00037506	0.00037506	0.00037506	0.00037506	0.00037506	0.00037509	0.00037509	0.00037502	0.00037502	0.000375	0.000375	0.000375	0.000375	0.000375	0.000375		
z (m)	2.4576E-05	2.4576E-05	2.4576E-05	2.4576E-05	2.4576E-05	2.4576E-05	2.4576E-05	2.4576E-05	2.4578E-05	2.4578E-05	2.4576E-05	2.4576E-05	2.4574E-05	2.4574E-05	2.4574E-05	2.4574E-05	2.4574E-05	2.4574E-05		
[K] d2 = 20 (µm)	300.025	303.671	325.243	367.609	427.048	497.321	574.3	654.078	734.881	814.743	893.196	969.214	1042.91	1113.72	1181.99	1247.35	1310.24	1370.39		
[K] d1 = 10 (µm)	382.007	693.19	944.958	1217.26	1411.4	1616.27	1760.4	1918.35	2028.31	2154.36	2240.91	2344.58	2414.35	2501.68	2559.12	2634.14	2682.25	2747.74		
Case B200: [200 ns on, 100 ns off]																				
Pulse #		1			2			3			4			5			6			
target condition (K)		5000	adb		5000	adb		5000	adb		5000	adb		5000	adb		5000	adb		
time (ns)	100	200	300	400	500	600	700	800	900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000
x2 (m)	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008		
x1 (m)	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009		
y (m)	0.00037501	0.00037501	0.00037501	0.00037501	0.00037501	0.00037501	0.00037501	0.00037501	0.00037501	0.00037501	0.00037501	0.00037501	0.00037501	0.00037501	0.00037501	0.00037501	0.00037501	0.00037501		
z (m)	2.4575E-05	2.4575E-05	2.4575E-05	2.4575E-05	2.4575E-05	2.4575E-05	2.4575E-05	2.4575E-05	2.4575E-05	2.4575E-05	2.4575E-05	2.4575E-05	2.4575E-05	2.4575E-05	2.4575E-05	2.4575E-05	2.4575E-05	2.4575E-05		
[K] d2 = 20 (µm)	300.034	303.88	326.712	374.927	439.923	515.569	598.704	683.538	768.188	852.656	934.241	1012.86	1089.46	1162.39	1232.02	1299.49	1363.51	1424.55		
[K] d1 = 10 (µm)	383.591	715.676	1049.16	1273.35	1512.47	1721.59	1857.72	2013.01	2152.69	2240.83	2350.85	2452.3	2513.31	2596.6	2674.8	2719.11	2785.19	2848.09		
Case B400: 400 ns on, 100 ns off]																				
Pulse #				1					2					3					4	
target condition (K)				5000	adb				5000	adb				5000	adb				5000	adb
time (ns)	100	200	300	400	500	600	700	800	900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000
x2 (m)	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008	0.00008
x1 (m)	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009	0.00009
y (m)	0.00037507	0.00037507	0.00037507	0.00037507	0.00037507	0.00037507	0.00037507	0.00037507	0.00037507	0.00037507	0.00037507	0.00037507	0.00037507	0.00037507	0.00037507	0.00037507	0.00037507	0.00037507	0.00037507	0.00037507
z (m)	2.458E-05	2.458E-05	2.458E-05	2.458E-05	2.458E-05	2.458E-05	2.458E-05	2.458E-05	2.458E-05	2.458E-05	2.4577E-05	2.4577E-05	2.4577E-05	2.4577E-05	2.4577E-05	2.4577E-05	2.4577E-05	2.4577E-05	2.4577E-05	2.4577E-05
[K] d2 = 20 (µm)	300.056	304.289	327.529	376.603	446.438	528.636	614.534	701.184	788.54	875.646	960.817	1041.46	1117.94	1191.86	1263.62	1332.65	1397.39	1458.47	1517.42	1574.69
[K] d1 = 10 (µm)	386.584	715.543	1064.54	1363.15	1597.79	1750.51	1918.52	2078.75	2219.66	2333.38	2403.24	2494.12	2587.05	2671.89	2740.66	2778.37	2836.86	2899.92	2958.67	3005.83

Appendix B

```
clear
clc

rho1=2700; %density of solid material kg/m^3)%
rho2=840; %density of ejected liquid and gas kg/m^3%
t=100e-9; %duration of pulse s%
r=.5/1000; % radius of target m%
d=.006/1000; % depth of melted material m%

v=d*pi*r^2; %m^3%
mdot=v*rho1/t; %kg/s%
V=mdot/((pi*r^2)*rho2) % m/s %
```

```
V =

  192.8571
```

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Appendix C

Contents


```
% Finite-Difference 2-D Axisymmetric Cylindrical Model of Heat Transfer
% that occurs from Laser Ablation of Aluminum using Isothermic boundary
% condition when laser is on and Adiabatic condition when laster is off.

% Target region is set to 5000 K
% Pulse duration is 100 ns with equal on/off duration

% Guidance was provided by Dr. Alex Povitsky

% Script was written by Arthur Pamboukis Spring 2019

% Other researchers: Max Hanich, Erika Nosal and Zachary Rahe,

clear all
```

Boundary Conditions / Input Parameters:

```
% Laser Properties / Target Conditons

Ttarget = 5000;      % temperature, K
Tamb = 300;          % temperature, K
Tend = Tamb;         % temperature, K

Pulse = 100e-9;      % duration of pulse, 100 ns
Pulses = 3;          % Number of Pulses


% Step Increments:

dt = 1e-9;          % time step, 1ns

dr = 2e-5;          % radial increment, 50 microns

dx = 6.5e-7;        % depth increment, .65 microns


% Aluminum Properties:

k = 237;                    % heat transfer coefficient, W/m-K

rho = 2700;                 % density, kg / m^3

Cp = 910;                   % Specific Heat, J / kg-K

alpha = k / (rho*Cp);       % Thermal diffusity, m^2/s


% Stability criteria

r1 = alpha * dt / dr^2;

r2 = alpha * dt / dx^2;

ratio = r1 + r2;            % step ratio, needs to be under .5 for stability


% Cylindrical Dimensions

L = 50*dx;                 % length of cylinder, 30 microns

D = 1e-3;                   % diameter of laser pulse, 1 mm

radius = D/2;               % radius of laser pulse, .5 mm

R = 2e-3;                   % measured diameter of rod, 2 mm
```

```
% Loop Inputs

Tloops = 2*Pulses;                % Total time loops given

Ploop = round(Pulse/dt);          % number of time steps

Rloop = round(R/dr);              % number of radial steps

Xloop = round(L/dx);              % number of depth steps


% Radial / Depth Vector:

RR = [0 : dr : R];          % Width of collumn, 40mm

XX = [0 : dx : L];          % Depth of collumn, 40mm
```

Pulse Calulations

```
for Np = 1 : Tloops                 % Tracks loop for each on / off of laser pulse

for P = (Np-1)*Ploop+1 : Np*Ploop   % Creates time increments for pulses

    for r = 1 : (Rloop + 1)         % Radial loop

        for x = 1 : (Xloop + 1)     % Depth loop

            if x == 1 && r >= 1 && r <= round(radius/dr + 1) && mod(Np,2) == 1          % Pulse is on, Target = 5000K

                T(x,r,P) = Ttarget;         % Sets Target Temperature of 5000K

            elseif x == 1 && r >= 1 && r <= round(radius/dr + 1) && mod(Np,2) == 0      % Pulse is off, Target Adiabatic

                T(x,r,P) = T(2,r,P-1);

            elseif x == (Xloop+1)

                T(x,r,P) = Tend;            % Sets Temperature at end of rod to ambient temperature, 300K

            elseif P == 1

                T(x,r,P) = Tamb;            % Initializes temperature of rod to ambient temperature except for Target

            elseif P > 1 && r == (Rloop +1)

                T(x,r,P) = Tamb;            % Condition for edge of collumn

            elseif P > 1 && x == 1  && r > round(radius/dr + 1)

                T(x,r,P) = Tamb;            % Sets surface temperature to ambient except at target area

            elseif r == 1 && x < Xloop + 1

                T(x,r,P) = T(x,r,P-1) + r2 * ( T(x+1,r,P-1) - 2*T(x,r,P-1) + T(x-1,r,P-1) );

                % Calculates temperature at axis of symmetry assuming
                % T(P+1) - T(P) = 0



            else

                T(x,r,P) = T(x,r,P-1) + r1 * ( dr/(2*radius) * ( T(x,r+1,P-1) - T(x,r-1,P-1) ) + ...
                    T(x,r+1,P-1) - 2*T(x,r,P-1) + T(x,r-1,P-1) ) + r2 * ( T(x+1,r,P-1) - 2*T(x,r,P-1) + T(x-1,r,P-1) );

            end

        end

    end

end
```

```
figure(1)

hold on

plot(XX,T(:,1,P))
title('Temperature along axis of symmetry')
xlabel('Depth (m)')
ylabel('Temperature (K)')

    if Np == 1

    str = {strcat('End of Pulse1')};

    elseif mod(Np,2) == 1

        str = [str,strcat('End of Pulse', num2str((Np+1)/2))];

    elseif mod(Np,2) == 0

        str = [str,strcat('100ns after Pulse', num2str(Np/2))];

    end

hold off

figure

contourf(RR,XX,T(:,:,P));
colorbar
xlabel('Surface (m)')
ylabel('Depth (m)')

    if mod(Np,2) == 1

        TITLE = strcat('End of Pulse', num2str((Np+1)/2));

    elseif mod(Np,2) == 0

        TITLE = strcat('100ns after Pulse', num2str(Np/2));

    end

title(TITLE)

end

figure(1)
legend(str(:))
```

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