Theoretical Study of Laser-assisted Machining on Silicon Nitride Hollow Ceramic Cylinder Using Finite Element Method

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ABSTRACT

THEORETICAL STUDY OF LASER ASSISTED MACHINING ON SILICON NITRIDE HOLLOW CERAMIC CYLINDER USING FINITE ELEMENT METHOD

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Northern Illinois University, 2018
Dr. Iman Salehinia, Thesis Director

The most commonly used technique for machining ceramics is diamond grinding. It accounts for up to 75% of the manufacturing costs resulting in high cost of the product. An LED bulb offering increased brightness, energy saving and long life by using ceramic integration to LED chips costs around 10 times a normal LED bulb. Complex geometries used in electronics, medical surgeries, aerospace, and automobile industries require the use of costly molds or powder metallurgy for low batch production, which does not justify the cost. Laser-assisted machining (LAM) is a process that uses a laser to locally heat the surface of a component (made of ceramic), making it more ductile and machinable using conventional machine tools. Recent studies have shown that LAM gives improved material removal rate and surface finishing and reduces the cost of machining to around 50% reduction in the manufacturing costs.

Physical experiments require the use of advanced instruments and specialized tool, making it a difficult and time-consuming process. It is necessary to have a predicting thermal study to help design more efficient physical experiments. In this study, finite element analysis (FEA) has been
used to analyze the thermal distribution of a workpiece under rotating and translating moving heat source.

In LAM, there are many variables that greatly affect the temperature, such as laser size, laser power, translational velocity, etc. Extensive research has been performed on solid cylinders; however, many new applications such as thermocouple protection tube, cylinder lining, blasting nozzles, bone fusion in surgeries, etc., require application of hollow cylinders. Therefore, this work performed a thermal study on a ceramic tube with a laser beam moving on its outer surface. As the generated heat due to the machining is insignificant compared to the heat created by the laser heat source, this study doesn’t consider the mechanical removal of the material. The ceramic chosen for this study is silicon nitride, as it is widely used due to its excellent wide range of properties making it suitable for all industries. The FEA method and assumptions that were used in this research has been verified with previous experimental and numerical research on a solid cylinder.
THEORETICAL STUDY OF LASER-ASSISTED MACHINING
ON SILICON NITRIDE HOLLOW CERAMIC CYLINDER
USING FINITE ELEMENT METHOD

BY

MOHAMMED MUDASSAR HUSSAIN ANSARI
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Thesis Director:
Iman Salehinia
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CHAPTER-1
INTRODUCTION

1.1 Motivation

During the past decade there have been many technological advancements and discoveries. This has enabled mankind to develop advanced materials such as super alloys based on titanium and nickel, advanced ceramics, chromium alloys, etc. These materials have different advantages, mainly providing high strength, surface hardness and heat-resistant properties which can be used in a multitude of industries such as nuclear, medical, electronics, automotive and aerospace industries (Venkatesan, 2014). Ceramics have generated quite a lot of interest due to versatile properties. The most common properties of ceramics are high hardness, wear resistance and melting point, corrosion resistance and low electrical conductivity. By the technological advancements ceramics can now be developed by mixing different oxides, nitrides and boron with different materials to obtain different ceramics with specific properties required for various applications. Due to this versatility and advantageous properties, ceramics are increasingly replacing metals in these industries.

However, in today’s industry, mass production plays an important role in selecting a material, and flexibility in machining is an important criterion in selecting the material for a specific application. Ceramics require some special machining techniques when compared to
conventional machining techniques and have not fully replaced metals. To address this situation, hybrid machine processes are being developed for ceramics. This research will be focusing on one such type of hybrid machining known as laser-assisted machining (LAM) and will study the underlying parameters needed to control this technique for machining ceramics and complex geometries.

1.2 Machining Methods of Ceramics

Ceramics are materials that are brittle in nature and possess high hardness. Conventional machine tools typically result in less material rate or else can result in surface cracks, brittle failure, and excessive tool wear in ceramics (Sinhoff, 2001); (Wagemann, 1993). Machining of ceramics can be very expensive due to its inability to be conventionally machined using machine tools and requiring advanced machining processes using expensive tools and technology (Uhlmann, Holl, Ardelt, & Laufer, 2007).

The most common technique used for machining ceramics is diamond grinding (Tuersley, 1994); Ultrasonic machining, direct casting method (Bergström, 2000) and electric discharge machining are machining techniques used to produce complex geometries with intricate designs. These methods result in high tool wear and dimensional inaccuracy resulting in further grinding to achieve the required dimension, which further increases the price of the finished product. Recent technological advancements include additive manufacturing and selective laser sintering (SLS), yet these techniques require high initial investment and the process time is slowed down due to the layer-by-layer machining process.
(Kopeliovich, 2012) reported the maximum material removal rate with diamond grinding as 9.832 mm³/min and the machining cost associated with diamond grinding for ceramics can be up to 75% of the total cost (Said, 1999). Even with the slow material removal rate, diamond grinding is the most popular machining technique used in industries for mass production. To encounter these limitations in machining ceramics, there is a need for hybrid machining techniques. One such technique is laser-assisted machining (LAM), which can be used in conjunction with conventional machine tools such as lathe, milling, and planning machines. In LAM, the laser is used to locally heat the ceramic, thereby making it suitable to machine conventionally. (Kopeliovich, 2012) reported a maximum material removal rate of 983 mm³/min, resulting in almost 10 times removal rate when compared to the diamond grinding. LAM is also anticipated to reduce the cost of machining ceramics by at least 50% (Shin, 2009) and is suitable for producing complex geometries. Figure 1 shows the lathe tool operation coupled with a laser at Purdue University.
1.3 Advanced Ceramics

According to (Kopeliovich, 2012), ceramics can be classified as traditional ceramics or advanced ceramics. Traditional ceramics can be used in clay products, kitchen wares, bricks and tiles, etc. Advanced ceramics, on the other hand, are used for engineering and medicine applications, as these materials have high mechanical and thermal strength, low density, and corrosion resistance in comparison to metals. Advanced ceramics can be classified to structural ceramics and electro-ceramics and can be further classified based on material into oxide ceramics, silicate ceramics, carbide ceramics, and nitride ceramics (Kopeliovich, 2012). Ceramics are used in various industries based on their properties. Silicon carbide is used in brake components of the automobile industry (Weimer, 1996), Alumina is used in medicine for bone fusion and hip
replacement surgeries (Taylor, 2003), and boron carbide is widely used in military applications for body armor and vehicle plating (Weimer, 1996). These are some of the examples of the many uses of advanced ceramics.

1.4 Silicon Nitride

Silicon nitride possesses high strength, toughness, and excellent thermal and is chemical stable, corrosion resistant and makes excellent alternative to metals. Good mechanical properties at higher temperatures mean that silicon nitride is a good material for turbines and automobile engines, as the material can withstand high thermal gradient, and mechanical stresses at high temperature while maintaining its structural integrity and properties (Materials, 2014). Through technological advancements, silicon nitride can be manufactured by different techniques, namely, reaction bonded, hot pressed, and powder sintering (Sciammarella, 2008). Different techniques result in change in the microstructure of silicon nitride, resulting in increased surface hardness and improved friction capabilities. This led silicon nitride to be used in bearing and rolling applications. The usage of silicon nitride as a bearing reduces the weight, eliminates need of lubrication due to less friction and has a higher expected life in comparison to metals. All these applications require tight geometrical tolerances and fine surface finishing. Silicon nitride being a ceramic material is brittle in nature, making conventional machining a difficult prospect as it can result in surface cracks or failure of machining tool. To achieve the required tolerances, grinding is the most favored technique in industries to machine ceramics. Diamond grinding is used because the hard surface of silicon nitride can be machined by the diamond tool without a high probability
of tool failure. However, this results in increased tool wear due to the lengthy machining duration and an expensive tool results in higher cost of the finished product.

1.5 Literature Review

For the better part of two decades, research has been going on for LAM. Studies have been focused on different machining techniques such as laser cutting, laser heat treatment, and laser forming. The parameters of these processes have been researched, established and developed to a point where the industries have been using these studies for their production. Numerous experimental and numerical studies have been done on LAM processes with different geometries and machine tools. The demand for ceramics continues to rise, requiring more complex and intricate geometries. Laser-assisted machining has faster machining time as reported by (Kopeliovich, 2012), better surface quality, and enables machining complex geometries, as will be shown in the following literature review. Brecher, Rosen and Emonts reported that almost 75% of the final cost of a ceramic component can be attributed to the diamond grinding process (Brecher, 2010). These limitations and disadvantages in machining led to the study of hybrid machining techniques to reduce the machining costs of ceramics. Ceramics when exposed to an external heat source acts like a ductile material due to the decrease in yield strength and enables plastic deformation (Yongho, 2012). Based on this material property, LAM has been developed where the external heat source used is a laser. The laser is used to heat the workpiece. Silicon nitride lowers its yield strength below the ceramic’s fracture strength, making the ceramic more ductile. This results in continuous chip formation during machining on the workpiece (Yongho, 2012). (Kopeliovich, 2012) reported increased material removal rates when compared to diamond
grinding and superior surface finish. In LAM, the temperature is of major importance as high temperatures can affect the microstructure of the ceramic, resulting in undesirable changes in properties; lower temperatures can result in the material not being ductile enough, affecting the tool and surface finish of the machined part (Chryssolouris, 1997). The process parameters that affect the quality of LAM significantly are laser spot size, laser power, workpiece rotation speed and size, and laser feed rate (Panuganti, 2009).

Laser-assisted machining is based on the theory that a laser heats the ceramic and lowers its yield strength, making the material ductile and easier to machine by reducing the cutting force and tool wear. (Estibaliz, 2009) conducted experiments on silicon nitride, alumina and zirconia to study the effect of temperature on yield strength. A contact test was performed on these ceramic materials using a universal testing machine and the magnitude of contact stress from the test was recorded and the results show the decrease in yield stress of these ceramic materials with the increase in temperature. Figure 2 shows the result of the contact test; a decrease in yield stress is seen as the temperature increases for silicon nitride and alumina, whereas the decrease in zirconia was not too much.
Figure 2 Effect of temperature on yield strength (Estibaliz, 2009)

(Chang & Kuo, 2007) performed LAM on cuboid Al$_2$O$_3$ and reported a 22% reduction in feed force, 20% reduction in thrust force, and better surface finish. This was performed on a planing machine. (Brecher, 2010) reported a reduction of 73% in cutting forces, 90% reduction in lateral force and 75% reduction in passive force. This experiment was performed on a milling machine that was modified to accommodate the laser equipment along with the pyrometer. The geometry of the ceramic was rectangular. In addition to reporting the decreased cutting forces, the sample was observed under an electron microscope and the sample revealed better surface finish and reduced tool wear when compared to machining of the sample without laser assistance. Figure
3(a) shows the cutting forces and microscopic images of no LAM being used and Figure 3(b) shows the results with LAM used.

![Figure 3 Comparison of cutting forces and surface finish (Brecher, 2010)](image)

An important parameter for numerical study of LAM is the value of absorptance coefficient of the material. (Zhang, 1998) conducted experiments for recording the absorptance of silicon nitride for the wavelength of the laser as a function of temperature. The experiment was conducted using a Nd:YAG and a CO\textsubscript{2} with wavelengths of 1.06\textmu m and 10.6\textmu m respectively. The reflectance of the material was measured through a focused laser probe and the temperature recorded through a pyrometer. The Nd:YAG laser showed a uniform absorptance of 0.83. The absorptance values while using the Nd:YAG laser with 1.06 \textmu m are almost constant, whereas the CO\textsubscript{2} laser with with 10.6\textmu m can be seen increasing in Figure 4.
Konig and Zaboklicki (1993) performed experiments on lathe machines and milling machines. For the lathe machine operation, Nd:YAG and CO₂ lasers were used with laser power 700W and 1100W respectively. For the milling machine operation, a CO₂ laser with a maximum power of 5.1kW was used. The ceramic workpieces were heated to a temperature of 1100°C, which is the glass phase change temperature for silicon nitride, and the results confirmed the reduction in cutting forces and increased surface finish (Konig & Zaboklicki, 1993). The data suggests that a surface finish between 3µm and 0.5µm can be obtained by LAM.

(Janvrin, 1996) developed a three-dimensional heat conduction model to predict the temperatures during LAM of silicon nitride to identify the rotational speed that results in optimum
temperature for cutting the material. This study was one of the first ones done towards the modeling of LAM using finite difference method and was based on a lot of assumptions such as neglecting radiation and convection heat loss and that properties of silicon nitride are temperature independent (Janvrin, 1996). These assumptions were not accurate, and the results obtained were not enough to understand the effect of operating parameters on LAM. (Shen, 2010) also developed a three-dimensional transient thermo-mechanical model to analyze the effect of LAM operating parameters, i.e., laser power, laser beam diameter, pre-heat time, and feed rate, on the temperature distribution and stresses in the workpiece and the tool. Convection and radiation were considered as modes of heat loss through the surface of the workpiece (Shen, 2010). The results conclude that pre-heat time is the time required for the temperature to rise to the glass transition phase change and the material ready for cutting operation; lower feed rate induced higher stresses.

(Jihong, 2010) conducted a study regarding the process parameters affecting the heat-affected zone based on a Ti<sub>6</sub>Al<sub>4</sub> ceramic during LAM. This three-dimensional finite element model was based on a Gaussian heat flux distribution which represents the heat flux distribution of a laser accurately. A good agreement between the results of FEM and experimental results was achieved at temperatures above 980°C, which is the required temperature for LAM.

Pfefferkorn (2004) and Panuganti (2009) conducted several experiments on LAM to determine the effect of operating parameters on ceramics. Pfefferkorn performed experiments as well as numerical models on partially stabilized zirconia. Panuganti performed the experiments on silicon nitride, and both papers studied the effect of operating process parameters on the temperatures in the ceramic workpiece. Pfefferkorn (2010) also studied the thermal conductivity
and specific heat of silicon nitride and published results of the change of these properties with change in temperature.

Purdue University has done extensive research on this topic and (Rozzi, 1997) have successfully performed experiments and numerical models for his dissertation on the topic of LAM on silicon nitride (Purdue). The study was focused on the effect of operating parameters on the temperature of the workpiece and the effect of stresses on the temperature and tool life when a tool was introduced to start the machining process.

Mohiuddin (2017) developed a finite element model based on Rozzi (1997). The heat flux in this study was estimated to be uniform. This study was focused on studying the thermal histories in the ceramic tube by changing the operating parameters of LAM. The important assumption of this study was that of heat loss through the inner surfaces, as the workpiece is hollow in nature. The effect of change in thickness of the geometry was also studied (Mohiuddin, 2017).

The aim of the current research is to develop a finite element model considering the Gaussian distribution of the heat flux, which is a more accurate representation of the heat flux distribution of laser in physical experiments. Based on the Gaussian distribution, the thermal distribution of the workpiece is studied. This study will consider hollow ceramic cylinders (tube), as most of the previous research was based on solid cylinders and cuboid geometry. The study of ceramic tubes can provide a foundation for machining complex and intricate geometries. The effect of operating parameters on the thermal distribution on the outer and inner surfaces of the
workpiece, and tool lag of the thermal distribution along the depth of a tube with varying thickness will be studied.
CHAPTER-2

FINITE ELEMENT MODEL

This thesis has used FEM to study the effects of an external heat source, laser, on temperature distribution in a silicon nitride tube. There are numerous tools available for FEA, and the software package used to perform these simulations is ANSYS APDL 18.1. The advantages of using ANSYS are that it is user-friendly and provides a GUI and a three-dimensional modeling interface where the user can easily build the model, apply the loading conditions and solve the model. The model used in this thesis has been completely modeled and solved in ANSYS. As with any FEA software, ANSYS requires a basic step-by-step process that must be followed for accurate results. The steps needed to perform a successful analysis are as follows (ANSYS, n.d.):

1. Modeling the geometry
2. Defining material properties
3. Discretizing of geometry in elements
4. Applying initial and boundary conditions of the simulation on the geometry
5. Applying the loading – heat flux
6. Solving model
2.1 Modeling of Geometry

The ANSYS environment is divided into different parts, consisting of utility menu, input window, toolbar, main menu, and graphics menu. ANSYS APDL has great versatility in being able to offer graphical representation as well as generating code for faster modeling of the geometry. The main menu contains the primary ANSYS functions; they are mainly preprocessor, solution and general postprocessing (ANSYS, n.d.). It is from this preprocessor menu that the modeling tools are used to model the geometry and generate the code behind the modeling. As this study is focused on cylindrical workpieces, the modeling controls have been used to input the required dimensions to design the cylindrical workpiece. Four different types of geometries are used in this thesis: one solid cylinder, used for verification of results with literature, and three tubes, which will be the focus of this study. Table 1 contains the different specifications of the geometries with the diameter and length of workpiece specified.

<table>
<thead>
<tr>
<th>Model</th>
<th>Outer Diameter (mm)</th>
<th>Inner Diameter (mm)</th>
<th>Length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid</td>
<td>8.4</td>
<td>0</td>
<td>25</td>
</tr>
<tr>
<td>Hollow</td>
<td>8.4</td>
<td>6mm, 4mm, 2mm</td>
<td>15.5</td>
</tr>
</tbody>
</table>

These dimensions can be entered in the preprocessor section of the main menu, and a 3D model will be generated as well as a code. This code can be saved and using this code will enable generating other model geometries faster by just changing the dimension in the code. Figures 5-8 depict a pictorial representation of the model generated by ANSYS, Figures 5 and 6 are solid models and Figures 7 and 8 are geometry of hollow cylinders. The geometry has been divided into
multiple volumes to provide greater control while meshing the model and easier analysis of data obtained while solving the model, which will be discussed later in this chapter.

Figure 5 Front view solid cylinder
Figure 6 Isometric view of solid cylinder

Figure 7 Front view of tube
2.2. Defining Material Properties

ANSYS is a software that simulates real-world engineering problems. As in the case of a physical experiment, the material has its own set of material properties that need to be provided in ANSYS for successfully solving the FEA model. As per the mathematical formulation, thermal conductivity, specific heat, density and absorptivity are required for this simulation. The thermal conductivity and specific heat for silicon nitride have been taken from (Pfefferkorn, 2010); the absorptivity is taken as 0.85 based on results of Zhang (1998); the density is taken as 3150 kg/m³ based on data available on Rozzi (1997). For silicon nitride, the values of specific heat and thermal
conduction are temperature dependent, (Table 2). Figures 9 and 10 show the relationship of these properties with temperature.

Table 2 Silicon Nitride Temperature Dependent Material Properties of Thermal Conductivity and Specific Heat (Pfefferkorn, 2010)

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>Thermal Conductivity (W/m-K)</th>
<th>Specific Heat (J/kg-K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>296</td>
<td>17.5</td>
<td>643.7</td>
</tr>
<tr>
<td>371</td>
<td>17.0</td>
<td>776.8</td>
</tr>
<tr>
<td>474</td>
<td>16.7</td>
<td>895.2</td>
</tr>
<tr>
<td>573</td>
<td>16.0</td>
<td>968.1</td>
</tr>
<tr>
<td>774</td>
<td>15.0</td>
<td>1044.6</td>
</tr>
<tr>
<td>873</td>
<td>14.5</td>
<td>1086.6</td>
</tr>
<tr>
<td>975</td>
<td>13.6</td>
<td>1115.7</td>
</tr>
<tr>
<td>1074</td>
<td>12.8</td>
<td>1137.6</td>
</tr>
<tr>
<td>1173</td>
<td>12.1</td>
<td>1157.6</td>
</tr>
<tr>
<td>1272</td>
<td>11.6</td>
<td>1172.2</td>
</tr>
<tr>
<td>1374</td>
<td>10.9</td>
<td>1183.1</td>
</tr>
<tr>
<td>1476</td>
<td>10.1</td>
<td>1190.4</td>
</tr>
<tr>
<td>1578</td>
<td>9.7</td>
<td>1199.5</td>
</tr>
<tr>
<td>Temperature (K)</td>
<td>Thermal Conductivity (W/m-K)</td>
<td>Specific Heat (J/kg-K)</td>
</tr>
<tr>
<td>----------------</td>
<td>-----------------------------</td>
<td>------------------------</td>
</tr>
<tr>
<td>1674</td>
<td>9.2</td>
<td>1206.8</td>
</tr>
<tr>
<td>1875</td>
<td>8.2</td>
<td>1210.5</td>
</tr>
<tr>
<td>1974</td>
<td>8.0</td>
<td>1214.1</td>
</tr>
</tbody>
</table>

Figure 9 Relation of Thermal Conductivity with Temperature of Silicon Nitride
2.3. Meshing

Once the geometry has been designed, it needs to be meshed. Meshing can be defined as the discretization of the body into a finite number of elements. Once meshing is performed, it will result in the creation of nodes and elements on which the loading and boundary conditions can be applied. A mapped or continuous mesh will result in an even distribution of the load and more accurate results can be obtained. Before meshing, it is necessary to specify the element type of the model. Since, we will be performing a transient thermal study on a 3D model, we have chosen the solid70 element type for our model from the ANSYS library (Figure 11) (www.ansys.stuba.sk,
n.d.). This type of element has eight nodes with only 1 degree of freedom, i.e., temperature at the nodes.

![Diagram of solid70 element in ANSYS](www.analystubadk.n.d.)

**Figure 11 Depiction of solid70 element in ANSYS (www.analystubadk.n.d.)**

A uniform division of the elements results in accurate results. This is called mapped meshing in ANSYS and this is the reason why we have divided the cylindrical body in four parts, as it gives more control over the meshing of the model. The meshing used was similar for both the solid and tube models as shown in the figures below. The different criteria for meshing are specified for the outer volume; this is the volume where the heat load will be applied, and it requires a finer mesh compared to the other sections of the volumes. The outer volume has been divided into $0.4^\circ$ circumferentially, four divisions along the radial face and 125 divisions along the axial length. These divisions result in a fine mesh due to which the convergence of load can be obtained. The outer volume is shown in Figure 12; Figure 13 is the middle section of the model and is divided $6^\circ$ circumferentially to reduce the number of elements. The innermost volume as
shown in Figure 14 is a free mesh and that has also resulted in an almost uniform mesh. A sweep mesh has been used to connect the outermost volume and the middle volume as there is a big change in the circumferential divisions as shown in Figure 15. Figure 16 is the front view of the solid cylinder.

*Figure 12 Mapped mesh on external surface of cylinder*
Figure 13 Mapped mesh of the middle volume

Figure 14 Free mesh of innermost volume
Figure 15 Sweep mesh connecting the outer volume and middle volume

Figure 16 Front view of solid cylinder
The meshing of the hollow cylinder is almost the same as the solid cylinder except for removal of the innermost volume. Figure 17 shows the front and isometric views of the hollow cylinder.

![Figure 17 Front and isometric views of hollow cylinder](image)

2.4. Initial and Boundary Conditions for the Model

Rozzi conducted many numerical and physical experiments on LAM of silicon nitride. Based on the literature provided; the following conditions were applied to the FEA model. Before
the LAM process is begun, it is assumed that the silicon nitride workpiece is in equilibrium with the room temperature, i.e., 25°C. The boundary conditions that are applied to the model are that of convection of free air with a convective heat transfer coefficient of 50W/m-K (Rozzi, 1997). Radiation heat losses were neglected for the FEA model as the maximum temperature is always beneath the laser and the time of each load step is less than 6 milliseconds (depending on rotation speed of workpiece, as low as 1.6 millisecond), which won’t have much impact if neglected. The convective heat transfer is applied in such a way that it covers the full surface of the model, except the region which will be covered by the laser. During this time, the region beneath the laser will be exposed to heat flux. To simulate an actual experiment, the translation of the laser was considered to have a 50% overlap over the region that it was covering in the previous load-step, as this relates to the continuous flow of the laser movement along the workpiece. The heat flux was calculated by referring to Rozzi (1997), by which Figure 18 was obtained. In ANSYS, varying heat flux cannot be given within a radius, but multiple heat fluxes can be given for multiple radii, which is shown in Figure 18. The red curve represents the actual laser heat flux distribution as reported by Rozzi (1997), and the blue curve is the actual distribution in ANSYS.
Another parameter to be calculated is the time of each full rotation of the workpiece and then dividing the time between load steps. A load step in ANSYS is considered the time during which the laser heats a certain spot and then moves to the next spot. This can be calculated by the rotation speed of the workpiece and then dividing it by the number of passes that the laser does to complete one full rotation of the workpiece as shown in the following equation.

\[
T_r = \frac{60}{\text{Workpiece Rotation Speed}} \text{ (sec)}
\]

2.5 Problem Statement

To perform successful machining of ceramics using LAM, the ceramic needs to be heated to its glass transition phase change (Konig & Zaboklicki, 1993). For the yttrium silicon aluminum
and oxy-nitride (YSiAlON) group of ceramics, under which silicon nitride is classified, the temperature is 920°C -980°C (Rozzi, 1997). During LAM, if the temperature in the workpiece is less than this required temperature, machining could result in surface cracks of the ceramic workpiece or the failure of the tool. If the temperature is much higher than required, this can cause an unintended change in the microstructure of the ceramic, altering its properties (Chryssolouris, 1997). Due to the importance of temperature during LAM, a thermal study is required to study the effect of LAM parameters on the temperature. The FEM study is used to predict the temperatures during LAM, and based on these predictions, experiment parameters can be performed.

2.6 Assumptions

While performing FEA analysis, some assumptions were taken into consideration due to certain computational limitations and to decrease the effective run time of the FEA analysis (Mohiuddin, 2017):

1. Isotropic material properties were considered.
2. Uniform distribution of heat flux was considered.
3. Constant absorptivity of the material was assumed.
4. Air acts as the convective fluid surrounding the workpiece.
5. Effect of radiation heat loss has been neglected.
6. Thermal conductivity and specific heat of the material vary along with the temperature (Mohiuddin, 2017).
2.7 Mathematical Model

The FEA analysis is based on mathematical equations, from which we can predict the curve of the thermal distribution. LAM is a process where many simultaneous processes can be recorded. The effect of various operating parameters adversely affects the temperature distribution within the ceramic. During the start of the process, the laser is the heat source and the energy is dissipated to the ceramic by radiation. As the laser radiation encounters the workpiece, it is converted into conduction and the heat travels through the ceramic through conduction, as can be seen in the results and discussion section. Heat conduction takes place within the volume of the workpiece in all directions (axial, circumferential and radial). Convective heat loss occurs from the external surfaces to the environment.

2.8 Numerical Equations

The FEA model is based on numerical equations, which means it is physically possible to perform the experiments and obtain results that can be validated by the numerical equations. In LAM, the workpiece is subjected to a moving heat source (i.e., laser); this can be written in the form of a transient three-dimensional conduction and circumferential convection. In a cylindrical coordinate system, the rate of change of temperature can be written by the equation (Rozzi, 1997):

\[
k \left\{ \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right) + \frac{1}{r^2} \frac{\partial}{\partial \phi} \left( \frac{\partial T}{\partial \phi} \right) + \frac{\partial}{\partial z} \left( \frac{\partial T}{\partial z} \right) \right\} - \frac{\partial (\rho c_p \omega T)}{\partial \phi} = \rho c_p \frac{dT}{dt}
\]
In the above equation, the thermal conductivity has been assumed as isotropic, which has been taken as an assumption in our FEA model, where $\rho$, $c_p$ and $k$ are the material properties density, specific heat, and thermal conductivity respectively. ‘$\omega$’ is the angular velocity, ‘$T$’ is the temperature, and ‘$t$’ is the time.

The boundary condition at the surface of the workpiece can be represented in equation for m by:

$$k \frac{\partial T}{\partial t} = \alpha_l q_l'' - q''_{conv} - E(T) + \alpha_{sur} G_{sur} (T_{sur})$$

where $\alpha$ is absorptivity coefficient of the laser and surface respectively. The radiation is represented by the E term; however, we have neglected that in the FEA model as the radiation is due to the laser. The radiation is between when the laser beam is emitted from the laser when it hits the surface of the workpiece, at which point it is converted to heat conduction. To avoid complex FEA models, and due to computational limitations, the radiation was neglected and only conduction and convection considered. The term $q''$ is the heat loss due to convection on the outer surface of the workpiece.

Thermal conduction of the heat absorbed within a volume is governed by the equation:

$$\nabla \cdot (k \nabla T) = \rho c \frac{dT}{dt}$$
For the initial conditions, the workpiece is exposed to the room temperature, which can be represented as the following equation represented in cylindrical coordinates at time equal to zero, meaning the initial condition, and $T_a$ is the ambient temperature to which the workpiece is exposed.

$$T(r, \varphi, z)_{t=0} = T_a$$

2.9 Mesh Convergence

ANSYS is an analysis tool, that requires the input of the model, boundary conditions, and loads to show you the result of your analysis. However, it is very easy to go wrong in ANSYS even with a slight mistake. One way of making sure the results are correct is mesh convergence especially in a transient heat analysis. The mesh convergence was performed for the solid model. The results of the mesh convergence can be seen in Figure 19, which shows the effect of the radial division on the model. A $2^\circ$ division along the circumference of the cylinder meant that the mesh was not perfect and there is a temperature drop below the initial condition, which is not physically possible. As the radial division kept getting smaller, the mesh convergence was stable at 298K at 0.4$^\circ$ division along the circumference of the cylinder.
An additional way to confirm the mesh convergence is to have a constant temperature with varying degrees of mesh refinement. Figure 16 shows the number of elements required to achieve the mesh convergence. This was due to Gaussian distribution being used to apply the heat flux, which meant that the heat flux was applied in division of radius and the divisions needed to be refined meshes so that the heat flux could be evenly distributed. This resulted with the mesh convergence needing almost 1 million elements to converge, as shown in Figure 20.
Figure 20 Mesh convergence for solid model
CHAPTER-3

RESULTS AND DISCUSSIONS

3.1 Model Verification

To verify that the FEA model was accurate and the Gaussian heat flux distribution was working as intended, the FEA model was verified with the results of Rozzi’s doctoral thesis. Rozzi performed in-depth LAM experiments and numerical analysis on LAM of Silicon Nitride. In Rozzi’s experiments, the temperature was recorded with the use of a pyrometer, and the temperature observed was then compared with the numerical results, which showed good agreement in both the methods (Rozzi, 1997).

The FEA model for verification has been designed on Rozzi’s model mentioned in his thesis. In Table.3 we can see the difference in the experimental model and the FEA model. The hemisphere in the experimental model has been modelled in the FEA as a plain cylinder to have symmetry along the length of the workpiece, and the length of the total geometry was reduced to have reduced element numbers in the FEA model. Since the time for which the experiment was being recorded, i.e., 10 seconds, the laser would not complete 20mm along the length of the workpiece, which is why 25mm length sufficed in the FEA model.
Rozzi recorded the temperature histories along three points of the length of the workpiece as seen in Figure 21. The points have been labeled as M1, M2, M3, with each point 5 mm apart from the other. M1 is at 8.33 mm from the start of the workpiece. The temperature has been recorded on these points as the laser traverses along the length of the workpiece for a time of 10

<table>
<thead>
<tr>
<th></th>
<th>Actual Model</th>
<th>Finite Element Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter (mm)</td>
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<td>8.46</td>
</tr>
<tr>
<td>Length (mm)</td>
<td>57</td>
<td>25</td>
</tr>
</tbody>
</table>

**Table 3 Comparison of J.C Rozzi's and FE Model (Rozzi, 1997)**

![Image](image_url)
seconds. The angle at which these points are is 67.7° from the center of the workpiece. This is taken keeping in view that the laser will be at this point when LAM begins.

![Diagram](image.png)

*Figure 21 Location of points of interest along the length of the workpiece (Rozzi, 1997)*

In Figure 22 we can see the thermal histories recorded on these three points. Rozzi’s thesis also provides information on the operating parameters used within this experiment. The laser was operating at a power of 500W and the laser diameter is 3mm. The workpiece rotation speed is 1000RPM and the feed rate of the laser along the length of the workpiece is 100mm/min (Rozzi, 1997). Figure.18 tells us that the numerical and experimental thermal values of Rozzi’s thesis are in good agreement. In Figure.23, the FEA model used for thesis is compared with the results of
Figure 22. The FEA model has good agreement with the numerical model, as can be seen in Figure 23.

Figure 22: Thermal histories at points M1, M2 and M3 (Rozzi, 1997)
Figure 23 Thermal histories for points M1, M2 and M3 comparing with FEA analysis of this thesis

From Figure 23 we can see that the FEA results agree with the results of Rozzi. A slight difference can be seen at the peaks of the graph; this is due to the unavailability of nodes at that exact location in the FEA model, and a node before the actual location had to be taken, which is why the FEA peak is a bit earlier than the curve of Rozzi. The agreement of the FEA analysis validates the assumptions of the Gaussian distribution of the heat flux and the FEA model.

3.2 Analysis of Operating Parameters on Tube Model

From the literature review, we learned that the operating parameters are the real parameters affecting the temperature of the ceramic workpiece. For this thesis, these parameters, namely, laser
Power, laser spot size, workpiece rotation speed, feed rate, and pre-heat time, are varied and the effects of these parameters on the tube have been studied using FEA. Several analyses have been performed using FEA, as shown in Table 4, to have a thermal study on all these parameters. In addition to these parameters, the temperature on the inside surface of the tube has also been analyzed to determine the temperature at the inside of the tube and the right time for machining to be started at the inner surface. This has been studied by varying the thickness and analyzing the temperatures (Mohiuddin, 2017).

Table 4 List of Cases Studied Using FEA on Ceramic Tubes

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Laser Power (W)</th>
<th>Laser Spot Size (mm)</th>
<th>Rotational Speed (RPM)</th>
<th>Feed Rate (mm/min)</th>
<th>Pre-Heat Time (sec)</th>
<th>Inner Diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>250</td>
<td>2.8</td>
<td>500</td>
<td>50</td>
<td>10</td>
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</tr>
<tr>
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<td>1.7</td>
<td>500</td>
<td>50</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>Case No.</td>
<td>Laser Power (W)</td>
<td>Laser Spot Size (mm)</td>
<td>Rotational Speed (RPM)</td>
<td>Feed Rate (mm/min)</td>
<td>Pre-Heat Time (sec)</td>
<td>Inner Diameter (mm)</td>
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<tr>
<td>Case No.</td>
<td>Laser Power (W)</td>
<td>Laser Spot Size (mm)</td>
<td>Rotational Speed (RPM)</td>
<td>Feed Rate (mm/min)</td>
<td>Pre-Heat Time (sec)</td>
<td>Inner Diameter (mm)</td>
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</tbody>
</table>

Effect of Pre-Heat Time:

In LAM, the pre-heat time can be described as increasing the temperature of the workpiece to allow uniform increase in the temperature as the laser starts to traverse along the length of workpiece. During pre-heat, the laser stays at the same spot axially, with the workpiece rotating and being heated. Cases 4, 5 and 9 vary in the amount of pre-heat time for the laser. The other processing parameters, which are kept constant to study the effect of different pre-heat times, are laser power (375W), laser spot size (2.8mm), workpiece rotation speed (500RPM) and feed rate (50mm/min). Figure 24 shows the plot of the variation of the maximum temperature of the workpiece with respect to time for the considered cases. From the plot after pre-heat, the temperatures drop a little as the laser starts to move axially. This is due to the temperature not being as high as it is under the laser. However, as the laser spends more time heating the workpiece, the temperature rises due to conduction within the workpiece. To avoid sudden heat changes while traversing axially, pre-heat is important for the overall temperature of the workpiece. Higher pre-heat time results in higher temperatures being induced in the workpiece, whereas a lower pre-
heating time results in lower temperatures in the workpiece and can be set according to the preference of machining. Thus, pre-heating has a huge impact on the amount of temperature raised with time in the workpiece.

![Temperature Vs Time](image)

*Figure 24 Effect of pre-heat time on ceramic tube*

Effect of Laser Power:

Laser power has the main impact on the amount of temperature induced in the workpiece, as it controls the amount of heat energy being directed to the workpiece. In FEA, the laser power is described as heat flux, and in this FEA model, the heat flux used was a Gaussian distribution. Figure 25 shows the plot of the variation of maximum temperature with respect to time for various laser powers (Cases 1, 5 and 12). The other process parameters were kept constant to study the effect of laser power, workpiece rotation speed: 500RPM, feed rate: 50mm/min, pre-heat time:
The effect of laser power is seen in Figure 25 as a higher power laser will result in higher temperature being induced in the workpiece.

![Temperature Vs Time](image)

*Figure 25 Effect of laser power on ceramic tube*

Effect of Laser Spot Size:

As in the previous case, the laser power is an important parameter in determining the temperature of the workpiece. The laser power can be affected by different diameters of the laser. The heat flux is inversely proportional to the laser size. As the diameter of the laser decreases, it means more power is being focused on a smaller distribution of area, resulting in higher temperature, whereas a bigger diameter laser spot means heat flux focused on a larger area,
resulting in less concentration of heat flux and lower temperature, as can be seen in Figure 26. Cases 5, 6, 12, and 13 have been studied to determine the effect of laser spot size on a ceramic tube. The process parameters have been kept constant for all four cases; with the only change being the laser diameter, which is 3mm and 1.7mm. The other process parameters are kept constant, which are laser power 500W and 375W (two different cases for laser powers), rotation speed 500RPM, feed rate 50mm/min and pre-heat time 10sec. Figure 26 shows the variation of maximum temperature with respect to time for the discussed in Cases 5, 6, 12 and 13. For both the powers 500W and 375W, similar trend can be observed in the maximum temperature.

*Figure 26 Effect of laser spot size on ceramic tube*
Effect of Workpiece Rotational Speed:

Machining requires the workpiece to be rotated at different speeds. For example, a threading operation requires the rotating speed to be minimal, whereas a turning operation requires high rotating speed. This operating parameter can have great temperature variation based on the rotating speeds. As the rotation speed (RPM) increases, it means the laser spends less time at each spot and results in lower temperature, whereas as the rotational speed decreases, the laser can spend more time on a spot and is able to induce more temperature in the workpiece, resulting in higher temperatures. In Figure 27, different rotational speeds have been studied. The different operating parameters have been kept constant: laser power 500W, feed rate 100mm/min, pre-heat time 10sec, laser spot size 2.8mm. Cases 11, 14 and 16 are the cases where the rotational speed is varied from 250RPM to 1000RPM. As predicted, the temperature is lower on higher rotation speed and higher at lower rotation speed, as can be seen in Figure 27.

![Figure 27 Effect of rotational speed on ceramic tube](image-url)
Effect of Feed Rate:

As in the previous case of rotating speed, the effect of feed rate, which is the speed of the axial velocity with which the laser traverses along the length of the workpiece, has the same effects with change in feed rate. Higher feed rate equals less time the workpiece is exposed to the laser, resulting in lower temperatures, whereas lower feed rate means laser spends more time heating the workpiece and results in higher temperatures. Feed rate can be set to machining preferences of surface finish and machining operations. Cases 5, 7, 12, and 14 have been studied for the effect of different feed rates 50mm/min and 100mm/min. The other process parameters have been kept constant, which are laser power 500W and 375W (two different cases), laser spot size 2.8mm, rotation speed 500RPM and pre-heat time as 10sec. As predicted, lower feed rate will result in a higher temperature than higher feed rate in Figure 28.

Figure 28 Effect of feed rate on ceramic tube
Effect of Workpiece Thickness:

This thesis is studying the thermal histories within a ceramic tube. The most important parameter of a tube can be the effect of workpiece thickness. Different models of varying thickness of workpiece were made to study the variation of temperature with respect to time. Based on the model, it is expected a model with thickness 4mm and 2mm should accumulate more heat and attain higher temperatures when compared to the model with 6mm thickness and solid model (zero thickness). This is because the 4mm and 2mm thick model has less volume when compared to the 6mm and solid model, thereby decreasing the amount of material subjected to the same amount of heat energy, which results in higher temperatures. To study the effect of thickness of workpiece, only the thickness has been changed, with four cases being a solid model, 6mm thick model, 4mm and 2mm thick models. The other operating parameters were kept constant as laser power 500W, laser spot size 2.8mm, rotation speed 500RPM, feed rate 50mm/min and pre-heat time 10sec. We can see the effect of thickness of workpiece in Figure 29 which are Cases 12, 17, 18 and 19. It is noticed as the amount of volume decreases, the maximum temperatures in the workpiece increases.
Till now no literature has studied the temperature distribution along the inner surface of a ceramic tube undergoing LAM process. This study will help in determining the temperature at the inside surface while the laser is being applied on the outer surface. The temperature travels through material and affects the inner surface. Based on this study, predictions can be made whether simultaneous machining of the inner surface can take place while the outer surface is being machined, resulting in increase in productivity. Figure 30 shows the effect of workpiece thickness on the inner surface temperature. The parameters used for this comparison were 500 RPM, feed rate of 50mm/min, and 10 second pre-heat with the thickness in models being changed.
Based on the figure, it can be said that as the thickness decreases, the inner surface temperature rises above the glass transition phase change temperature for silicon nitride, which is around 920°C-970°C, thus making the inner surface suitable to machining at the same time as the outer surface. For cases where the thickness is high, more pre-heat may be required so that the temperature will reach the glass transition phase change. However, the study on the maximum temperature on the outer surface is of critical importance, as the temperature will rise above the melting temperature, which means it will not be favorable to machine the inside surface with such a high-powered laser. The laser power must be varied so that the outer maximum temperature stays within the limits.
Thermal Study of Tool Lag:

In LAM, the machining tool is required to be behind the laser at a distance that can be determined by this study. This is mainly done for two reasons, as the tool should not be too close to the laser so that it can be affected by the laser energy and the temperature on the workpiece must be suitable for machining, which can be determined from this study. Tool lag is of two types, with one being at the outer surface studying the maximum temperature and the other being at the depth of cut. It is an important study as it can determine the temperature at the depth of cut, thereby determining the temperature at the inside of the workpiece. This is the reason that the FEA workpiece was divided in four volumes with the outer two volumes separated by 0.05mm, which is the depth of cut. The thermal history of the depth of cut is necessary to determine the machining lag, for if the temperature is not favorable for machining it will result in cracks in the surface of the workpiece or failure of the tool.

The machining temperature of silicon nitride is known as glass transition phase temperature, which is around 920°C-970°C. The tool lag can determine the maximum temperature behind the laser, and it can be determined at which point the machining can be started. Figure 31 is a 3-D plot showing the temperature, time and lag. After pre-heat, the most suitable lag to start machining is between 20-35° behind the laser. However, as time progresses, the temperature in the workpiece increases and the machining can be done even with a lag of above 45°. Figure 31 shows the temperature of the whole model, whereas Figure 32 shows the temperature above the required machining temperature and is easily understood.
Figure 31 Tool lag study at outer surface of all temperature at outer surface

Figure 32 Tool lag study at outer surface showing suitable lag above machining temperature
CHAPTER-4

CONCLUSION

This thesis was aimed to develop a transient three-dimensional FEA model using Gaussian distribution of heat flux to predict the temperature profile in a silicon nitride ceramic tube and provide insight of the variation of temperature due to different LAM parameters. The effect of these parameters was studied as well as variation in the thickness of the tube on the thermal history.

Pre-heat is an important step in performing LAM, as it helps the workpiece to gradually attain a stable temperature at which machining is possible. Different times of pre-heat have been studied and concluded that an optimum time for pre-heat is the time required for the ceramic to reach its glass phase transition temperature at which machining can be performed easily. Neglecting of pre-heat may result in insufficient temperatures and sudden spikes in temperature that may adversely affect the workpiece.

From the results obtained after studying the feed rate and rotation speed, we can conclude that the effects of these two parameters are the same on the temperature. As these parameters increase in speed, the temperature generated will be lower because the laser will be spending less amount of time at a region, which results in lower temperature. However, low speeds mean that the laser will spend more time at each load step and tend to increase the temperature. The machining operation taking place will need to consider these parameters for effective machining.
Laser power is directly associated with the rise of temperature, as it is the main source of heat generation. The power given to the workpiece can be controlled by the laser power.

Laser spot size is also directly proportional to the laser power. Heat flux can generally be calculated by the size of the laser spot diameter and the laser power. A smaller diameter means concentration of the heat flux at a smaller region, thereby resulting in higher temperatures even for the same power with different laser spot sizes.

The thickness of the ceramic tube is an important factor because the less thick the workpiece is, the less material there is available to absorb the laser energy and results in higher temperature. However, this can be also used to effectively machine the inner surface of the workpiece depending on the thickness and temperature profile.

4.1 Future Work

Preparing an FEA model with Gaussian distribution helped to accurately simulate a physical experiment theoretically. This provides an understanding of the temperature profile in ceramic tubes. This thesis provides a dynamic code that can be used for different models that study the temperature profile of ceramic tubes. Future work would be to introduce the tooling mechanism into the LAM environment and study the stresses on the workpiece as well as the tool. This will help to determine the possible failure causes and tool lag angles. Another way the research can be pushed further is by considering two lasers heating the workpiece instead of one and may result in no lag for the tool to start machining. The temperature profile provided by this thesis on the inner surface of the ceramic tube can also be used for LAM boring operations.
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