NUMERICAL INVESTIGATION OF THERMAL DAMAGE DURING LASER DRILLING PROCESS

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This thesis work is dedicated to:

My beloved mother Smt. Abha Rani Roy &

My beloved father Sri. Lakshman Chandra Roy

&

My respected supervisor Dr. Paramasivan K

ABSTRACT

NUMERICAL INVESTIGATION OF THERMAL DAMAGE DURING LASER DRILLING PROCESS

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Laser drilling is an advanced non-contact machining process which is a preferred choice in industrial applications due to its several advantages like precise hole, high positional accuracy, high repeatability etc. Geometry of the drilled hole like hole diameter and depth are important characteristics that greatly influence the quality of a drilled hole. In this work, a numerical model of transient heat transfer and thermal damage evaluation in Poly-methyl methacrylate (PMMA) material is presented using COMSOL Multiphysics®. Required material properties for the model are taken from available literatures. PMMA was selected due to its uniformity, isotropy, and the ease of characterizing its decomposition from solid to gas. A Gaussian heat flux is modeled and used as high energy laser beam. Ablation temperature of the material is considered as 698 k. The removal of material is modeled using deformed geometry interface module which is available in comsol multiphysics. After modelling, the parametric study has been done by varying laser power, beam diameter, and plater thickness to investigate about the thermal damage in terms of hole diameter and depth. To conduct the parametric study, central composite design (CCD) based design of experiment (DOE) has been generated using Design-Expert® software. 3D surface plots and contour plots are presented and discussed to illustrate the effect of input parameters on responses. It can be concluded from the results that laser power and spot diameter have a significant effect on drilled hole depth and hole diameter.

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INTRODUCTION

1.1. Background

Laser drilling is a precise method of removing material that uses concentrated laser beams to create holes in various materials. This process has become immensely popular in industries such as aerospace, electronics, medical devices, and manufacturing due to its ability to produce high-quality, accurate holes with minimal thermal damage and mechanical stress on the material.

The historical development of laser drilling can be traced back to the early 1960s, following the invention of the laser. Initially, lasers were mainly used for scientific research, but it soon became apparent that they had significant potential for industrial applications. Early laser drilling techniques involved the use of continuous-wave lasers, which emitted a constant beam of energy. However, the introduction of pulsed lasers, such as the Nd (Neodymium-doped Yttrium Aluminium Garnet) laser, marked a significant advancement in the process. These pulsed lasers offered higher peak power and greater control over the drilling parameters, leading to improved precision and efficiency in the drilling process.

In conclusion, laser drilling has revolutionized the way holes are created in materials, offering a high level of accuracy and quality while minimizing damage to the material. The evolution of laser technology, particularly the introduction of pulsed lasers, has greatly improved the efficiency and effectiveness of the drilling process. As a result, laser drilling has become an essential technique in a wide range of industries, playing a crucial role in the production of complex and precise components.

1.2. Laser Machining

Laser machining, a material extracting technique engaging thermal energy use in manufacturing units, is an extra advantage, where machining is tough to cut the materials, or create small holes and create a slot in asymmetric shaped materials. Laser machining is a non-contact, non-traditional and more flexible machining technique that uses thermal energy to remove the extra material from the desired workplace. Laser machining with a high intensity of laser beam of different widths is used for different types of applications such as cutting and making holes. Laser machining techniques involve conventional and fiber optic beam delivery systems, which permit precision positioning while cutting materials. Materials which have more brittleness and have thermal properties, such as low thermal diffusivity and conductivity, are particularly well suited for laser machining.

1.3 Laser Drilling

The definition of drilling is the process of creating a circular hole of specified depth and diameter by extracting metal at the circular edges of a drill bit. The drill machine is used for making circular holes. A tool is applied to make drill holes of different sizes called drill bit. Circular holes can be made on various surfaces, from wood to metal.

1.3.1 Principal of laser drilling

Laser drilling operates under a delicate energy equilibrium involving various factors such as the laser beam's irradiation energy, conduction heat into the work-piece, energy losses via convection and radiation, and the energy needed for a phase change within the work-piece.

In this process, a laser beam with specific characteristics is directed towards the work-piece, where some of the radiation is absorbed, leading to rapid heating and material evaporation. This results in the formation of a keyhole within the melting pool, maintained under pressure and assumed to radiate heat efficiently. Material vaporization leads to the creation of a plasma and the ejection of a jet of material in a perpendicular direction to the surface, while the surrounding area undergoes structural changes known as the Heat Affected Zone (HAZ) [7].

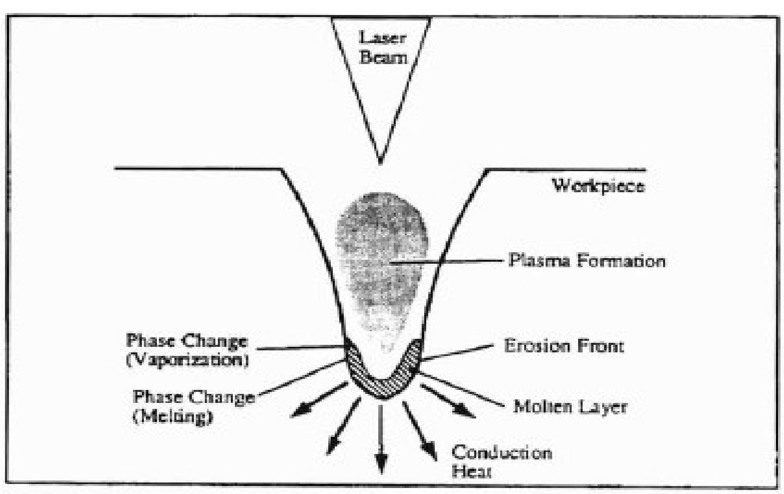

Figure 1: Laser Drilling Mechanism. [2]

After the laser pulse, a recast layer forms on the walls and bottom of the hole, containing disintegrated products and possessing different properties from the base material. In cases of defocused laser beams, there is a decrease in laser power, impacting vaporization rates and pressure, resulting in incomplete expulsion of melt from the hole. This intricate interplay of energy dynamics defines the intricate process of laser drilling.

1.3.2 Factors effecting laser drilling

The effectiveness of laser drilling processes is influenced by various factors related to pulse duration, power density, intensity profile, and stability of laser radiation parameters. Longer pulses exceeding 1 ms can hinder drilling control and lead to increased variability in hole sizes. They may also induce structural changes and cracking in brittle materials due to large heat-affected zones and thermal stress.

Fluctuations in power density during the pulse can compromise drilling accuracy and quality. Additionally, variations in the intensity profile of the laser beam play a significant role in determining the size and shape of the hole. The symmetric decrease of laser radiation from the center to the periphery of the beam can result in holes of regular shape but with molten edges and entrance conicity.

Factors such as instability in laser radiation parameters like energy, pulse duration, divergence angle, and beam structure can impact the reproducibility of the drilling process. Steady-state laser operation tends to produce identical holes, while the variability in hole size during single-pulse drilling is mainly attributed to laser pulse parameter instability in the steady-state regime.

Moreover, the surface reflectivity and physical properties of the work-piece material also have a notable effect on the laser drilling process. Therefore, it is crucial to consider and address these various factors to enhance the precision and efficiency of laser drilling operations.

1.3.3 Classification of laser drilling

Laser drilling is a process that involves using a high-power laser beam to make small, precise holes in various materials. There are several classifications of laser drilling, based on the type of laser used and the method of drilling.

One classification is based on the type of laser used, which can include solid-state lasers, gas lasers, and semiconductor lasers. Each type of laser has its own advantages and limitations, depending on factors such as power output, wavelength, and cost.

Another classification is based on the method of drilling, which can include percussion drilling, trepanning drilling, and helical drilling. Percussion drilling involves pulsing the laser beam to create a series of small holes, while trepanning drilling uses a rotating beam to create larger holes. Helical drilling involves moving the laser beam in a circular pattern to create spiral-shaped holes.

Overall, the classification of laser drilling is important for understanding the different techniques and applications of this process. By considering the type of laser and method of drilling, manufacturers can choose the best approach for their specific needs.

The easiest process is to remove material through a single pulse laser. The method is mainly used for drilling small holes through thin plates. One of the main applications of laser drilling is in the manufacturing industry, where it is used to create intricate patterns and shapes in various materials such as metals, plastics, and ceramics. The precision of laser drilling allows for the creation of holes with diameters as small as a few microns, making it ideal for applications where tight tolerances are required. In addition to manufacturing, laser drilling is also used in the aerospace industry for creating cooling holes in turbine blades and other components. These holes are essential for ensuring proper airflow and heat dissipation, and laser drilling provides a reliable and efficient way to create them.

Overall, the application of laser drilling has had a significant impact on various industries, enabling the production of complex components with unprecedented precision and efficiency. As technology continues to advance, we can expect to see even more innovative uses for laser drilling in the future.

Another technique used to drill wider holes in plates is to cut a contour out of the plate. That method is called laser trepanning drilling. And the drilling technique where the laser drive continues with a short pulse between 10-12 to 10-3 s, which is divided by long periods of time, is called laser percussion drilling. It is a more expensive drilling process. By laser drilling can be done, small holes with extreme precision (up to 0.002 micro-meters), high aspect ratios can be possible.

1.3.4 Application of laser drilling

Laser drilling is a cutting-edge technology that has revolutionized various industries by providing a precise and efficient method for creating holes in a wide range of materials. The versatility and accuracy of laser drilling make it a crucial tool in applications where precision is of utmost importance.

In the aerospace industry, laser drilling is commonly used to create cooling holes in turbine blades and other high-temperature components. These holes help regulate the temperature of the components, ensuring optimal performance and longevity of the equipment. The precision of laser drilling allows for the creation of intricate hole patterns that can effectively manage heat distribution in these critical components.

In the electronics industry, laser drilling is essential for creating micro vias in printed circuit boards (PCBs) and microelectronics for interconnects. These tiny holes allow for the connection of different layers of the PCB, enabling the miniaturization of electronic devices while maintaining high performance. The precision and speed of laser drilling are crucial in the production of complex electronic components that require tight tolerances.

In the medical devices sector, laser drilling plays a crucial role in manufacturing surgical instruments, stents, and other medical components that demand high precision. The ability to create fine holes with minimal heat-affected zones makes laser drilling ideal for producing intricate medical devices that meet stringent quality standards. The precise nature of laser drilling ensures that medical components are accurately manufactured, enhancing patient safety and treatment outcomes.

In the manufacturing industry, laser drilling is used to create fine holes in materials like ceramics, metals, and polymers for filters, nozzles, and other industrial applications. The speed and accuracy of laser drilling make it an ideal solution for producing complex parts with tight specifications. Whether it's creating micro-holes in ceramic filters or drilling precise nozzles in metal components, laser drilling offers manufacturers a high-quality and efficient method for producing intricate parts.

Laser drilling is a valuable technology that has significantly impacted various industries by providing a precise and efficient method for creating holes in a wide range of materials. From aerospace and electronics to medical devices and manufacturing, the applications of laser drilling are diverse and essential for achieving high precision and efficiency in modern production processes. As technology continues to advance, laser drilling will undoubtedly play an increasingly important role in meeting the evolving needs of industries that require precision and accuracy in their manufacturing processes.

1.3.5 Advantages and limitation of Laser Drilling

Laser drilling offers numerous advantages that make it a preferred choice for many industrial applications. Firstly, it excels in precision and accuracy by creating small, precise holes with high positional accuracy. This ensures minimal deviation and high repeatability, making it ideal for mass production. Additionally, laser drilling is a non-contact process, which reduces the risk of deformation, wear, and contamination by not applying mechanical force. This makes it suitable for brittle or delicate materials.

Moreover, the versatility of laser drilling is commendable as it is effective on a wide range of materials such as metals, ceramics, polymers, and composites. It can drill through various thicknesses and create holes with different diameters. Speed is also an advantage, as laser drilling is faster than traditional mechanical drilling, especially for small and micro-sized holes, enhancing productivity in high-volume manufacturing. The high aspect ratio of holes produced by laser drilling makes it suitable for deep and narrow holes.

While laser drilling has numerous advantages, it also comes with some limitations that must be considered. One limitation is thermal damage, as excessive heat can cause issues like recast layers and micro-cracks. Careful control of laser parameters is necessary to mitigate such damage. Another limitation is the high initial cost associated with advanced laser systems, as they require a significant investment and maintenance expenses.

Furthermore, laser drilling may have limited effectiveness on very thick materials, where mechanical drilling might be a better option. Material-specific challenges can also arise, as different materials require specific parameter adjustments. Additionally, the complex equipment and safety requirements of laser drilling demand specialized knowledge and strict adherence to protective measures to ensure safe operation.

In conclusion, laser drilling offers a multitude of advantages in terms of precision, accuracy, non-contact processing, versatility, speed, and high aspect ratio. However, its limitations such as thermal damage, high initial cost, material-specific challenges, and safety requirements must be considered when choosing laser drilling as a manufacturing process. Proper understanding of both the advantages and limitations of laser drilling is essential for making informed decisions in industrial applications.

1.4 Materials for Laser Drilling

Laser drilling is a versatile process that can be used on a variety of materials, each with its own unique characteristics that impact the drilling process. When selecting materials for laser drilling, it is important to consider factors such as thermal properties, reflectivity, absorption coefficient, and mechanical properties.

Metals such as stainless steel, aluminum, titanium, and copper each require specific laser parameters to ensure effective drilling without causing thermal damage. Ceramics like alumina and zirconia are known for their hardness and thermal stability, making them suitable for precise laser drilling. Polymers like PMMA, polycarbonate, and polyimide have relatively low melting points and can be easily drilled with lasers.

Composites like CFRPs and GFRPs require precise laser control to avoid damaging the fibers and matrix. Semiconductors like silicon and GaAs also require precise laser parameters to maintain the integrity of microelectronic structures. Glass materials like borosilicate glass and fused silica are suitable for laser drilling due to their thermal properties and transparency.

Considerations for material selection include the material's thermal conductivity, reflectivity, absorption coefficient, and mechanical properties. Materials with high thermal conductivity dissipate heat quickly, while materials with low thermal conductivity can concentrate heat and potentially lead to thermal damage. Highly reflective materials require specific laser wavelengths or higher power for efficient absorption, while the absorption coefficient determines the efficiency of the drilling process.

Conventional machining operations cannot be performed on composites due to their anisotropy, inhomogeneous composition. Hardness and abrasiveness. In such a case, laser drilling offers the advantages of high machining rates, no tool wear, no contact forces and relatively high precision.

In conclusion, selecting the right material for laser drilling is crucial for achieving high-quality results. Careful consideration of a material's properties and how they interact with laser energy will ensure an effective and efficient drilling process.

Chapter 2

NON-LINEAR MATERIAL PROPERTIES

2.1. Thermo-physical properties of laser drilling

Thermo-physical properties play a crucial role in the study of laser drilling [12]. Laser drilling is a sophisticated process that requires a deep understanding of the interactions between the laser beam and the material being drilled. The thermo physical properties of the material, such as thermal conductivity, melting point, and specific heat capacity, determine how the material will respond to the intense heat generated by the laser beam. These properties affect the rate of heat transfer, the depth of the drilled hole, and the overall quality of the drilled surface. For example, materials with high thermal conductivity will disperse heat more efficiently, resulting in faster drilling speeds and cleaner holes. On the other hand, materials with low thermal conductivity may require longer drilling times and may be prone to thermal damage. By studying the thermo physical properties of the material, researchers can optimize laser drilling parameters to achieve the desired results. This knowledge is essential for industries such as aerospace, automotive, and electronics, where precision drilling is critical for producing high-quality components. The thermo physical properties of materials is essential for successful laser drilling studies. By taking these properties into account, researchers can improve drilling efficiency, quality, and overall performance.

2.2. Density

Density is a fundamental property in the realm of materials science, defined as the mass per unit volume in the SI system, typically measured in kilograms per cubic meter (kg/m3). The density of pure metals and their alloys is known to vary with temperature, a crucial consideration in various industrial processes such as drilling using a heat source. Temperature plays a pivotal role in determining density, as the material undergoes thermal expansion when heated and contraction when cooled.

With an increase in temperature, the density of a material tends to decrease due to volumetric thermal expansion. For instance, at room temperature, the density of a solid typically stands at 7874 kg/m3. However, as the temperature rises, this density gradually decreases, eventually reaching 6980 kg/m3 in the liquid state near the melting point.

While the density of a solid at room temperature can be easily obtained from property tables, information regarding density variations with increasing temperatures is not always readily available in standard material handbooks. This lack of data becomes particularly significant in scenarios where the temperature surpasses the material's melting point, leading to phase changes during processes like laser cutting, drilling, and welding. Incorporating these phase change phenomena into finite element simulations requires the use of methods that account for apparent specific heat capacity in the two-phase zone to ensure accurate modelling of the entire process.[6]

$$k = k_{liquid}(1 - \alpha(T)) + k_{gas}(\alpha(T)) \qquad \ldots\ldots(1)$$

$$\rho = \rho_{liquid}(1 - \alpha(T)) + \rho_{gas}(\alpha(T)) \qquad \ldots\ldots\ldots(2)$$

$$Cp = Cp_{,liquid}(1 - \alpha(T)) + Cp_{gas}(\alpha(T)) + L_f \, \delta\alpha / \delta T \qquad \ldots\ldots(3)$$

Equations (1), (2), and (3) provide a framework for calculating the density of a material at different temperatures, taking into account factors such as thermal expansion and phase changes. The relationship between temperature and density is evident in the behaviour of materials like liquid iron and titanium, where increasing temperature results in a decrease in density due to thermal expansion.

In the context of laser drilling processes, it becomes imperative to accurately compute the melt behaviour by utilizing nonlinear material properties, data fitting techniques, and approximate solutions for unknown densities, especially up to the material's boiling point. This comprehensive approach ensures a thorough understanding of how density variations impact the overall behaviour of materials during high-temperature processes.

In conclusion, the intricate interplay between temperature and density underscores the importance of considering thermal effects when analysing material properties and behaviour. By incorporating these factors into simulations and calculations, researchers and engineers can gain valuable insights into how materials respond to heat and pressure, ultimately facilitating the optimization of various industrial processes.

2.3 Specific Heat

The study of heat capacity and specific heat in materials plays a crucial role in understanding how temperature affects the internal energy and volume changes in metals and alloys. When the temperature of a material increases, it results in an increase in internal energy and volume change due to heat, leading to external work. Heat capacity, denoted as C, is a physical quantity that measures the effect of thermal energy accumulation, where Q represents the heat energy added or removed, and C is the heat capacity of the material. In the SI system, heat capacity is expressed in units of [J/K], indicating the ability of a material to absorb heat energy for a one-degree change in temperature.

Specific heat, which is the heat capacity per unit mass, is divided into two categories based on whether the measurement is done at constant volume (Cv) or constant pressure (Cp). The specific heat at constant pressure (Cp) is more suitable for materials like metals and alloys due to their thermal expansion characteristics. The relationship between specific heat at constant pressure (Cp) and specific heat at constant volume (Cv) can be expressed using Mayer's relation, $Cp = Cv + Ru$, where Cp and Cv are heat capacities not yet divided by unit mass, and Ru is the universal gas constant.

In the context of laser drilling research, the specific heat at constant pressure is preferred to maintain stability in the melt pool under atmospheric pressure conditions. Understanding the correlation between enthalpy (H) and heat capacity is essential for determining specific heat over a wide range of temperatures. Enthalpy, as a measure of internal energy including external work at constant pressure, is a state function indicating thermodynamic potential in chemical and physical reactions. The relationship between enthalpy change (ΔH) and temperature change (ΔT) can be expressed mathematically using the equation $\Delta H = Cp\Delta T$. This equation demonstrates the change in enthalpy as a function of temperature, with specific heat at constant pressure (Cp) representing the rate of change of enthalpy with temperature at constant pressure.

In summary, the study of heat capacity, specific heat, and enthalpy is essential for understanding how materials respond to temperature changes and energy transfer. By investigating these thermodynamic properties, researchers can gain insights into the behaviour of materials under different thermal conditions and transitions between phases.

2.4 Conduction, radiation, and thermal conductivity

Conduction, as a fundamental method of transferring thermal energy through direct contact of materials, plays a crucial role in various

$$(\overrightarrow{Q} \; / \; A) = \overrightarrow{q} = - k \nabla T \qquad \dots\dots\dots\dots\dots(4)$$

processes, including drilling. At the heart of heat conduction lies Fourier's law, expressed mathematically as equation (4), where the heat flux (q) is proportional to the negative of the thermal conductivity (k) multiplied by the temperature difference (ΔT).

The thermal conductivity (k) represents the material's ability to conduct heat and is measured in watts per meter-kelvin [W/m•K] in the SI system. Heat flux, denoted by [W/m2], is the ratio of thermal energy (Q) to the area (A) through which heat is transferred. A temperature gradient within a material induces heat conduction, with heat always flowing from regions of higher energy to lower energy levels.

$$q = \varepsilon\sigma(T^4 - T_v{}^4) = \varepsilon\sigma(T^2 + T_v{}^2)(T + T_v)(T - T_v) = h_r(T - T_v) \quad \dots\dots\dots\dots\dots(5)$$

Furthermore, equation (5) introduces radiation heat transfer Fig.2 where the radiation heat coefficient (hr) is expressed as a function of temperature (T) and the surrounding medium temperature (Tv). Combining convection and radiation heat transfer, as per Newton's Law of Cooling, yields the overall heat transfer coefficient. In processes involving melt flow, such as in a melt pool, convectional heat exchange is correlated with the overall heat transfer coefficient, with radiation playing a predominant role due to the high melt temperatures.

In conclusion, understanding the principles of heat conduction, thermal conductivity, and radiation heat transfer is essential in various industrial processes, such as drilling and materials processing. By applying mathematical expressions and fundamental laws, engineers and researchers can optimize heat transfer mechanisms for improved efficiency and performance in thermal applications.

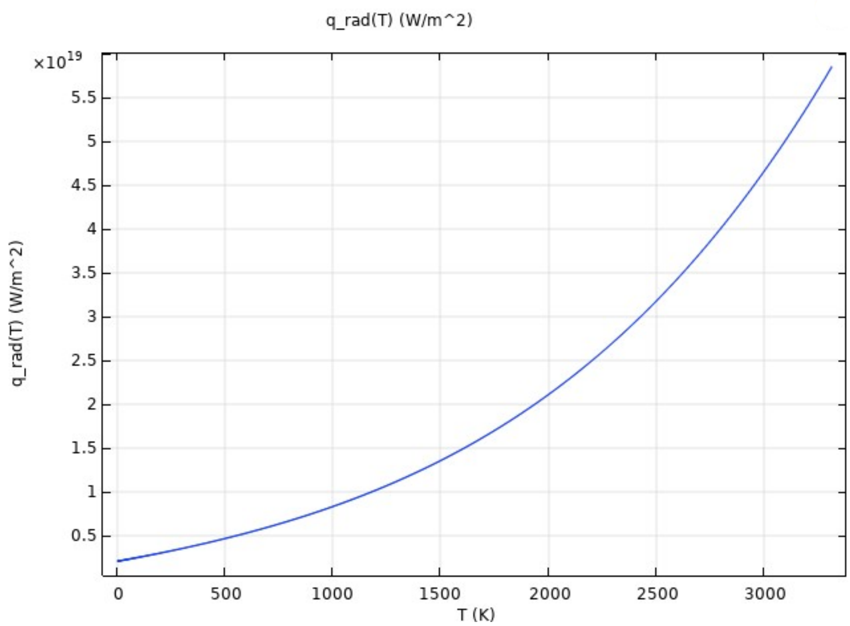

Figure 2: Radiation heat transfer over the free surface with time.

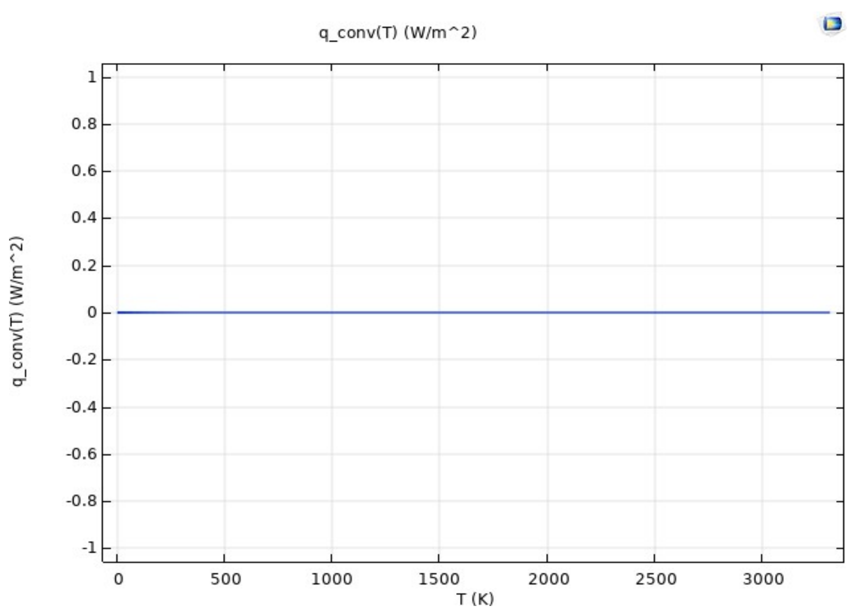

Figure 3: Convection heat transfer over the free surface and side surface with time.

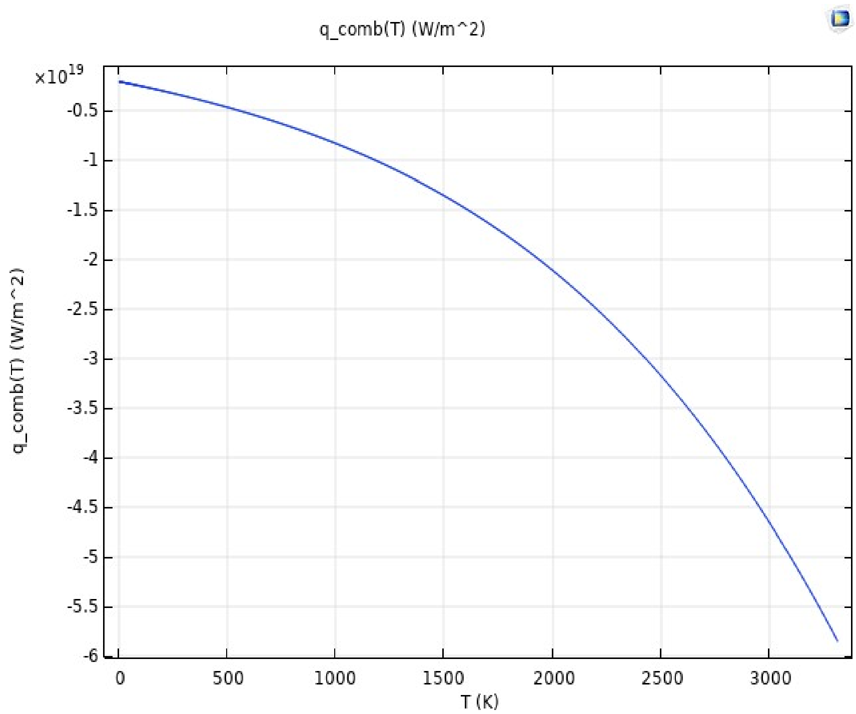

Figure 4: Convection heat transfer and radiation heat transfer over the free surface withtime.

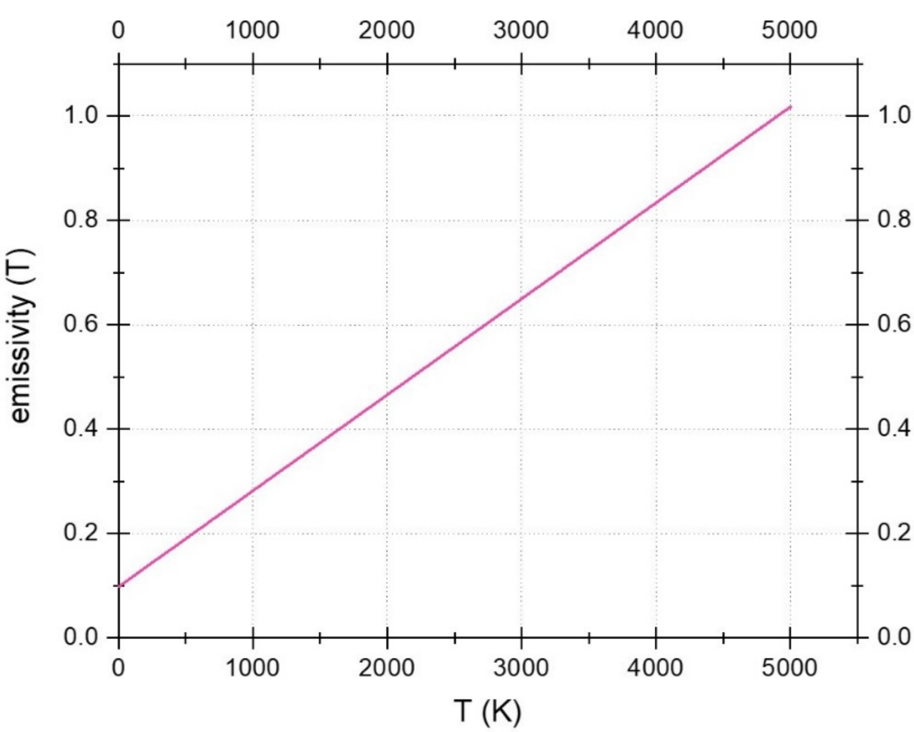

Figure 5: Emissivity as a function of temperature

2.5 Dimensionless numbers associated

I. The Nusselt number (Nu) serves as a crucial metric for quantifying the heat convection that transpires at the thermal boundary between liquid and gas within a melt pool. It is expressed as a function of dimensionless parameters, namely the Reynolds number (Re) and the Prandtl number (Pr), denoted as $Nu = hD / k = f(Re, Pr)$. Defined as the ratio of convective to conductive heat transfer across the thermal boundary, the average heat transfer coefficient can be determined by leveraging the Nusselt number, which can be calculated as $Nu = hD / k = f(Re, Pr)$. Understanding the overall heat transfer coefficient is imperative for enhancing the accuracy of heat transfer rate predictions across the liquid-gas boundary.

II. The Prandtl number (Pr) is characterized as the ratio of momentum diffusivity to thermal diffusivity, represented as $Pr = (\nu / \alpha) = (\mu Cp)/K$. It plays a pivotal role in delineating the heat transfer characteristics of a fluid.

Several assumptions must be taken into account when delving into these concepts. Firstly, the overall heat transfer rate is contingent upon the property values averaged between the temperatures of liquid and vapor iron. Secondly, the pool velocities must be conducive to ensuring an appropriate Reynolds number calculation.

In conclusion, the Nusselt number and Prandtl number are indispensable tools in the realm of thermal convection and heat transfer analysis. By comprehending and applying these parameters effectively, engineers and researchers can gain valuable insights into the intricate dynamics of heat transfer processes, thereby facilitating more accurate predictions and optimizations in various industrial and scientific applications.

2.6 Coefficient of thermal expansion

Thermal expansion is a fundamental concept in physics that describes the change in volume of a material in response to changes in temperature. When a material is heated or cooled, its volume tends to increase or decrease, respectively. This phenomenon is governed by the amount of thermal energy supplied to the system, which is directly proportional to the work done by the system. The rate of thermal expansion is therefore directly proportional to the magnitude of temperature change.

$$\alpha_v=(1/V)*(\delta V/ \delta T)_P \qquad \text{....................(6)}$$

The mathematical expression for the rate of thermal expansion, as given in equation (6), is applicable to various states of matter, including solids, liquids, and gases. Different coefficients of thermal expansion, such as volumetric, area, or linear expansion coefficients, can be used depending on the specific dimension of interest. In cases where a material expands uniformly in all directions, the volumetric thermal expansion can be simplified to linear thermal expansion.

$$\alpha_l=(1/L)*(\delta V/\ \delta T) \qquad \text{...................}(7)$$

In the context of finite element-based laser drilling analysis, equation (7) becomes more practical due to the adoption of an isotropic thermal expansion coefficient. Here, α represents the thermal expansion coefficient, δL is the rate of elongation per degree change in temperature, and αL signifies the fractional increase in length for a one-degree change in temperature.

$$\alpha_v = 3\alpha_l \qquad \text{……………….}(8)$$

Equation (8) highlights the relationship between volumetric and linear thermal expansion coefficients, where αv and αl denote the volumetric and linear coefficients, respectively. The ratio of 3:1 between these coefficients arises from the fact that a unit volume is composed of three equal unit lengths in Cartesian coordinates (V = L^3). By considering infinitesimal changes in volume and length, the thermal effect on volume change can be expressed through the relationship outlined in equation (8)In conclusion, the study of thermal expansion and its mathematical representations are crucial for understanding how materials respond to changes in temperature. By employing appropriate thermal expansion coefficients and equations, engineers and scientists can effectively predict and analyse the behaviour of materials under varying thermal conditions

Chapter 3

DESIGN OF EXPERIMENT & STATISTICAL ANALYSIS

3.1 Design of Experiments (DOE)

Design of Experiments (DOE) is a systematic approach to conducting experiments in order to optimize and improve processes. The history of DOE can be traced back to the early 20th century, with its roots in the work of Sir Ronald Fisher, an eminent statistician. Fisher's pioneering work laid the foundation for modern experimental design by introducing concepts such as randomization, replication, and blocking. These principles revolutionized the field of statistics and had a profound impact on various scientific disciplines, including agriculture, engineering, and medicine.

Over the years, DOE has evolved and expanded, with researchers developing new methodologies and techniques to address complex experimental problems. Today, DOE is widely used in industries ranging from manufacturing to healthcare to help businesses make informed decisions and improve their processes. Design of experiments (DOE) is a systematic and efficient method used by scientists and engineers to study the relationship between multiple input variables, also known as factors, and key output variables, also known as responses. DOE is a structured approach for collecting data and making discoveries in a scientific and systematic manner.

The advantages of using DOE is that it allows researchers to systematically vary input variables in order to study their effect on the output variables. By manipulating the input variables in a controlled manner, researchers can identify the key factors that have the greatest impact on the output variables. This information can then be used to optimize processes, improve product quality, and make informed decisions. Another important feature of DOE is its ability to provide insights into interactions between different factors. In many cases, the effect of a single factor on the output variable may depend on the levels of other factors. DOE allows researchers to study these interactions and determine how they influence the overall outcome. This information can be crucial for understanding complex systems and developing effective strategies for improvement.

Furthermore, DOE is a highly efficient method for conducting experiments. By utilizing statistical techniques and carefully designed experimental designs, researchers can obtain meaningful results with a minimum number of experiments. This not only reduces the time and resources required for experimentation but also allows researchers to make informed decisions quickly and effectively.

The central composite design (CCD) is the most commonly used fractional factorial design used in the response surface model. In this design, the center points are augmented with a group of axial points called star points. With this design, quickly first-order and second-order terms can be estimated.

Design of Experiments (DOE) is a statistical tool that is used in various industries to determine the effect of factors on a response. There are several instances when DOE can be beneficial:

a) DOE is used when we want to determine whether a factor or a group of factors have an impact on the response variable. By controlling and manipulating these factors, we can understand their influence on the outcome.

b) DOE is helpful in studying interactions between different factors. It allows us to see how factors may interact with each other to produce a certain response.

c) DOE helps in modelling the relationship between the response variable and the factors. This modelling can provide valuable insights into the behaviour of the response and aid in making informed decisions.

d) DOE can be used for optimization purposes. By conducting experiments and analysing the results, we can identify the optimal levels of factors that will produce the desired response.

In conclusion, Design of Experiments is a powerful tool that can be used in a variety of scenarios to determine factors' effects, study interactions, model relationships, and optimize responses. Its application can lead to improved processes, increased efficiency, and better decision-making in various industries.

3.2 Response Surface Methodology (RSM)

Response surface methodology (RSM) [2] is a powerful tool developed by George E. P. Box and K. B. Wilson in 1951 for modelling and optimizing experimental designs where a response is influenced by multiple variables. In practical applications, such as cooking quality dependent on heat source and ingredients, RSM can be used to enhance the response variable by optimizing the independent variables.

Response Surface Methodology (RSM) is a statistical technique that is commonly employed in regression analysis to analyse and optimize data. It is a powerful tool used to model interactions between multiple variables and determine the optimal settings for achieving desired outcomes. RSM is particularly useful in scientific and engineering fields where experimentation and data analysis are crucial for developing and improving processes. By using mathematical models and experimental data, RSM can help researchers identify the critical factors that affect a process and determine the optimal conditions for maximizing performance

One of the main benefits of using RSM is its ability to provide valuable insights into the interactions between variables. By fitting mathematical models to experimental data, researchers can identify the optimal settings for each variable, leading to improved efficiency and cost-effectiveness. Additionally, RSM can help researchers identify influential factors and their impact on the system, enabling them to prioritize resources and focus on areas that will have the greatest impact..

Response surface methodology (RSM) is a valuable tool for optimizing the quality of a process or product when there are multiple variables at play. In the case of regular cooking, the heat source (X1) and availability of ingredients (X2) are key factors that influence the cooking quality (Y). By utilizing RSM, these variables can be systematically varied to find the optimal combination those results in the highest quality outcome.

When X1 and X2 form a continuous range of values, RSM can help in developing and optimizing the cooking quality as a response variable. This statistical approach as

$$Y = f(X1, X2) + \varepsilon. \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(i)}$$

Experimental error, denoted by the symbol ε, is a crucial aspect of scientific research. In addition to experimental error, there are other factors that may not be accounted for in the calculation of the variable f. The independent variables are X1 and X2. In many Response Surface Methodology (RSM) problems, the response function (f) is often unknown and needs to be estimated. One common approach is to start by using a lower order polynomial to represent the response values. If the response can be adequately defined by a linear function, then the model is known as a first order model.

A first order model with two independent variables (X1, X2) can be expressed as a simple linear equation. This type of model is useful for understanding the relationship between the independent variables and the response, and can help in predicting the response values based on the input variables.

$$Y = \beta 0 + \beta_1 X_1 + \beta_2 X_2 + \varepsilon \quad \text{.. (ii)}$$

the intercept coefficient (β0) and partial regression coefficients (β1 and β2) play a crucial role in understanding the relationship between independent and dependent variables. β1 signifies the impact on the dependent variable when variable X1 is altered by one unit, with the remaining independent variables unchanged.

Following expression is the function of 2 independent variables (X1, X2) and is called second order model.

$$Y = \beta 0 + \beta 1X1 + \beta 2X2 + \beta 11X11\ 2 + \beta 22X22\ 2 + \beta 1\ \beta 2X1\ X2 + \varepsilon \quad \text{........... (iii)}$$

Mathematically expression (ii) or (iii) or merge these two expression can be used in RSM technique.

In the field of research and statistical modelling (RSM), the first motto is to identify the optimal response. This involves determining the best possible outcome when faced with multiple responses. It is crucial to pinpoint the optimal value for maximum efficiency and effectiveness.

The second motto focuses on comprehending how responses vary in relation to independent variables. By analysing these changes, researchers can gain valuable insights into the underlying dynamics of a system. Graphical visualization is a powerful tool that can aid in interpreting these variations and trends.

Overall, Response Surface Methodology is a valuable tool for researchers and engineers seeking to optimize processes and improve outcomes. By employing regression analysis and modelling techniques, RSM can help identify critical factors, optimize process conditions, and ultimately enhance performance. Its systematic approach to data analysis and experimentation makes it a valuable asset for anyone looking to maximize efficiency and effectiveness in their work

3.3 RSM in DOE

The design of experiments (DOE) stands as a crucial initial step in Response Surface Methodology (RSM). The primary aim of DOE is to pinpoint the most effective independent variable points for thorough examination of responses. The selection of the correct DOE significantly influences the creation of a response surface. Two main types of RSM designs are Central Composite Design (CCD) and Box-Behnken Design (BBD).

A) Central Composite Design (CCD) is a commonly utilized method that combines factorial or fractional factorial designs with center points and a set of axial points. This design allows for the fitting of a quadratic model and is often employed in sequential experimental work. With up to 5 levels per factor, CCD may include axial points outside the designated space, making it challenging to implement those points.

B) Box-Behnken Design: BBD is preferred in scenarios where cost efficiency is a crucial factor, as it generates a smaller set of design points with an equal number of factors. Unlike CCD, BBD lacks fractional or embedded factorial designs, making it less suitable for sequential experimental work. This design incorporates midpoints of the edges of the experimental space and necessitates at least 16 continuous factors, ensuring all points fall within the defined space. Notably, in BBD, all factors are not simultaneously set at their highest level.

In conclusion, the selection of the appropriate DOE, whether CCD or BBD, is pivotal in shaping the outcome of RSM studies, influencing the accuracy and efficiency of the experimental process.

3.4 Analysis of Variance (ANOVA)

Analysis of Variance (ANOVA) is a powerful statistical tool developed by statistician and evolutionary biologist Ronald Fisher. Its main purpose is to determine the significance of experimental results by comparing the variation between different groups. By analysing the input parameters of an experiment, ANOVA helps researchers identify the most influential factors affecting the outcome.

One of the key components of ANOVA is the F-test, which compares the variability within groups to the variability between groups. A standard F-value of 0.05 is typically used to determine significance at a 5% level. Additionally, the associated P-value should be less than 0.05 to validate the statistical model.

Degrees of freedom (DF) play a crucial role in ANOVA by indicating the number of observations in a sample. The DF of a term reflects the amount of information it contributes to the model, while the total DF represents the overall information in the sample. Adjusted sums of squares (Adj. SS) measure the variation between different elements in a model, while adjusted mean squares (Adj MS) account for the variation explained by the degrees of freedom.

The coefficient of determination, or R-squared, is a statistical measure that assesses the fit of a model to the data. It ranges from 0% to 100%, with higher values indicating a better fit. Adjusted R-squared (R-sq adj.) quantifies the percentage of variation in the dependent variable explained by the model, while predicted R-squared (R-sq pred.) assesses how accurately the model predicts outcomes for new observations.

Standard deviation is another important metric in ANOVA, quantifying the distance between data values and predicted values. A lower standard deviation indicates that the predicted values closely match the experimental data.

In conclusion, ANOVA is a valuable statistical technique that helps researchers analyse the significance and effectiveness of their experimental results. By considering the F-test, degrees of freedom, adjusted sums of squares, and various measures of variation, researchers can gain valuable insights into the factors influencing their outcomes. Ultimately, ANOVA provides a systematic approach to evaluating experimental data and making informed decisions based on statistical analysis.

Chapter 4

LITERATURE REVIEW

Hao Jiang *et al.* [1] used femtosecond laser to make a cylindrical hole in CFRP. They studied the effect of laser power, rotational speed of the laser and number of spiral passes on HAZ and ablation depth in circular laser drilling and spiral laser drilling mode. They analysed the forming process of laser drilling depth in the spiral drilling mode, laser energy, drilling feed, depth of holes, diameter and taper. And they concluded that the cylindrical hole of CFRP with a depth to diameter ratio 3:1 (Taper<32˚, HAZ<10μm) was obtained by using femtosecond laser.

S. Marimuthu *et al.* [2] used millisecond-pulsed-Quasi-CW-fibre laser space nickel super alloy. They aimed at mainly Quasi-CW-fibre laser parameters for trepanning laser drilled hole quality and speed. They have focused on controlling the recast layer oxide layer hole surface characteristics and fatigue performance of the laser drilled samples. And they get the result that the high average power of the Quasi-CW-fibre laser can be effectively used to achieve increased trepanning drilling speed without undermining the drilling quality. Also, low peak power and high frequency can be effectively used to produce better laser drill holes than high peak power and low frequency . Recast layer thickness around 30μm can be achieved with trepanning speed up to 500mm/min with a single orbit Quasi-CW-fibre laser drilling of a 0.75mm hole over a 5mm thick material.

Helen Elkington, Sundar Marimuthu and Bethan Smith [3] investigated the basic characteristic of a water-jet guided laser drilling process using a high characteristics laser (400W) to drill with a 0.7mm diameter angular hole (60˚ to the surface through 1.6mm thick nickel super alloy(resultant hole 1.85). On the experimental trail they used 148W laser power. They get the result that water jet pressure and average power are significant in controlling the recast layer and drilling cycle time. At higher power, the average recast layer thickness of 30μm is obtained with a cycle time of 3 seconds.

Un-Chul Paek and Francis Gagliano [4] in their early research on the thermal analysis of laser drilling, Paek and Gagliano developed a model that took into account continuous, distributed, and moving heat sources to describe temperature profiles and thermal stress propagation in drilled holes. Additionally, they identified the optimal laser drilling parameters.

Nasiru I Ibrahim *et al.* [5] in their study, Yilbas and Sahin investigated laser pulse optimization for practical laser drilling by converting process parameters into dimensionless groups. They utilized the Buckingham Pi theorem for dimensional analysis to obtain an optimum shape function from these dimensionless groups. The analysis was conducted considering both constant and variable physical properties.

William M Steen and Jyotirmoy Mazumder [6] developed a three-dimensional finite element model for laser material processing using a moving heat source with a Gaussian distribution profile. The model accounted for the keyhole effect by treating it as a black body. Assumptions included quasi-steady-state conditions after keyhole formation and surface heat losses on the upper and lower surfaces of the slab. The model successfully predicted fusion, heat-affected zones, and thermal cycles near a laser surface interaction.

Muammel M. Hanon *et al.* [7] in his study investigates the simulation of laser drilling processes on Inconel X-750 and Ti-5Al-2.5Sn sheets using COMSOL Multiphysics 5.2 software. A JK 701 pulsed Nd:YAG laser was utilized to drill through 2 mm and 3 mm thick plates of the mentioned materials with millisecond laser pulses. Various combinations of laser parameters, including peak power (10-20 kW) and pulse duration (0.5-2.5 ms), were examined to achieve controlled drilling through the entire thickness of the plates.

The study focused on analysing the temperature distribution on the cross-section of the images obtained in the simulation tests to determine the effects of these parameters. The research aimed to identify optimal conditions that enhance hole quality. Results indicated that increasing laser peak power and pulse duration led to linear growth in hole diameter and depth.

P.P.S. Keerthi and M. Sreenivasa Rao [8] investigated the effects of laser parameters on PMMA, with a Gaussian laser beam profile and moving heat source model. Laser micro-material processing (LMM) is a versatile method. PMMA (polymethyl Methacrylate) is commonly used in biomedical applications due to its non-toxic properties and ease of processing. In laser micromachining, material is removed through localized melting and evaporation. LMM involves thermal energy, resulting in thermal stresses and heat-affected zones. The research evaluated temperature distribution and heat-affected zones for different laser powers.

Ansam E. Abdulwahab *et al.* [9] study on micro-drilling was carried out on polycarbonate (PC) using a continuous CO2 laser. The choice of a CO2 laser machine was due to the PC's strong absorption of the 10.6µm wavelength, leading to quicker fabrication times and cost-effective laser systems. By employing a CO2 laser with a power range of 2-4 W and exposure time of 0.1-0.2s, the study analysed the effects of laser power, exposure time, and focal plane position on the drilling process. Results indicated that optimal drilling occurred at 2W power and 0.1s exposure time, producing a 0.55 mm depth with minimal heat affected zone.

Sharizal Ahmad Sobri *et al.* [10] experimented with the effect of machining parameters of CFRP (thickness 25.4 mm) using a fibre laser. They are using different types of laser machining criteria to assess the fibre laser ability to drill thick CFRP composite. The experimental result was that a fibre laser was able to penetrate a thick CFRP up to 22mm using novel drilling methods.

V. Chengal Reddy *et al.* [11] worked on optimized surface roughness and HAZ in fibre laser drilling of AISI 303 material using Taguchi-based grey relational analysis (GRA). From GRA methodology, recommended process parameters are flushing pressure (30 Pa), laser power 2000W and frequency 1500Hz for simultaneous optimization. From analysis, the pulse frequency is the most influenced process parameter in laser drilling techniques.

HE Cline and TRF Anthony [12] conducted a thermal analysis focusing on laser heating and melting of work materials utilizing a circular shaped heat source with a Gaussian beam profile. Their investigation involved a moving heat source with a constant velocity. Through a parametric analysis, they delved into the intricate dynamics of this process.

MF Modest and H Abakians [13] conducted a study on partial surface vaporization of a semi-infinite medium induced by a moving laser beam. In their research, they successfully solved two simultaneous nonlinear partial differential equations that encompassed three distinct regimes of a laser grooving process. This achievement was made possible through the derivation of boundary conditions for the first regime utilizing the Runge-Kutta routine. The complexity and depth of their analysis shed light on the intricate dynamics of laser-material interactions, further advancing our understanding of this phenomenon.

S Tosto [14] conducted a study on a 3D analytical model for pulsed-laser-induced ablation was presented. Unlike traditional models that rely on predefined beam intensity profiles like

Gaussian or Top Hat, Tosto's model defined the beam intensity through the careful selection of appropriate boundary conditions. This innovative approach potentially opens up new avenues for understanding and predicting pulsed-laser-induced ablation processes with greater accuracy and flexibility.

J.J. Radice *et al.* [15] a study on modeling heat transfer and thermochemical damage in carbon black-loaded PMMA using COMSOL Multiphysics. Previous research has detailed PMMA's thermal properties and behavior under laser irradiation. PMMA vaporizes between 310°C and 475°C, absorbing over half the energy from a 1070 nm Nd:YAG laser. This study uses these properties to simulate material ablation with temperature and phase-dependent properties, avoiding adaptive meshing. The results are compared to experiments, enhancing predictive accuracy for laser-material interactions.

PMMA (Polymethyl methacrylate) was selected for a study on thermal damage during laser drilling for its exceptional optical clarity, high light transmission, and conductive thermal properties to controlled heating and cooling responses. Its ease of processing, widespread industrial use, availability, and cost-effectiveness further support its suitability for detailed research on laser processing effects. The existing knowledge base on PMMA enhances the accuracy of modelling and predicting its behaviour in laser drilling processes, making it an ideal choice for investigating thermal damage.

The present work is planned with the following main objectives:

1. Presenting a numerical model of laser drilling in PMMA material
2. Numerically investigate the thermal damage during the laser drilling process
3. Studying the effect of process parameters on the hole diameters such as drilled hole diameter and hole depth
4. Statistically investigate the significance of the results

Chapter 5

FUNDAMENTAL STUDY ON LASER DRILLING MODEL

Numerical laser drilling [14] is a widely used technique in the manufacturing industry. It involves using a laser beam to drill precise holes in a metal surface. In this process, a heat source is placed on top of the free surface, at the co-ordinate (0 mm, 0 mm) with the reference point taken from the base corner left point. The heat source is static on the top surface of a base metal.

To model this process, a 2D axisymmetric cross-section model is used. This is because it is much more efficient to perform a fast computation in 2D than in 3D. The use of fewer elements usually consumes less computation time in numerical simulation. This is a significant advantage, as it allows for faster and more accurate simulations.

The 2D axisymmetric cross-section model is based on the assumption that the geometry of the object being drilled is symmetric about an axis. This allows for a simplified model that is easier to compute. The model takes into account the material properties of the metal being drilled, the laser beam parameters, and the heat transfer between the metal and the laser beam. The numerical simulation of laser drilling involves solving a set of partial differential equations that describe the heat transfer and material deformation. The solution to these equations gives the temperature distribution and material deformation in the metal. From this, the size and shape of the hole can be determined.

The accuracy of the numerical simulation depends on the quality of the model used. The 2D axisymmetric cross-section model is a good approximation for many laser drilling applications. However, for more complex geometries, a 3D model may be necessary to accurately capture the physics of the process.

The numerical laser drilling is an important process in the manufacturing industry. The use of a 2D axisymmetric cross-section model is a useful tool for simulating the process and predicting the size and shape of the drilled hole. The efficiency of this model makes it a popular choice for many applications. However, it is important to consider the limitations of the model and use a more complex model when necessary.

In the realm of computational simulations, the intricate web of governing equations finds its computational foundation in COMSOL Multiphysics 5.5. The meticulous calculations

conducted on a PMMA material platform, within an axisymmetric model, stand as a testament to the precision and depth of modern scientific inquiry.
The properties of the model have been meticulously categorized by numerous esteemed authors, underscoring the collaborative and iterative nature of scientific knowledge advancement. Within this framework, the axial symmetric space coordinate system is elegantly denoted as (r, z), while time finds its notation as t, encapsulating the essence of spatiotemporal dynamics.

The unknowns using in model are of the following :
- the temperature field noted T(r, z, t) ;
- the velocity field noted u(r, z, t) ;
- the pressure field P(r, z, t) .

PROPERTY	SYMBOL	VALUE
PMMA Density	ρ_s	1070 kg/m^3
PMMA ThermalConductivity	K	0.19 W/mK
PMMA Specific Heat	$C_{p,s}$	1470 J/kg-k
Latent Heat of PhaseChange	Δ_h	620 kJ/kg
ConvectionCoefficient	h	25W/m^2
Emissivity	ε	0.85
Phase Change EndTemperature	T_1	310˚C
Phase Change StartTemperature	T_2	475˚C
Reflectivity	$R_{\%}$	0.45
Laser Power	P	15 W to 40 W
Beam Diameter	D	4 mm to 6 mm
Plate Thickness	H	5 mm to 10 mm

Table 1: Thermo-Physical PMMA Material Property

5.1. Thermal Modelling

Energy balance serves as the foundational principle for elucidating the intricate dynamics of heat transfer systems. In the realm of modelling laser keyhole drilling of metals, a profound comprehension of the energy balance within the crucial interaction zone between the laser beam and matter stands as the linchpin. This understanding is pivotal for accurately simulating and predicting the intricate processes involved in this technological application.

When endeavouring to assess the temperature distribution across the entire domain over time, the energy equation is meticulously solved in a convection/diffusion format.

$$PC_p \frac{\partial t}{\partial t} + (u.\nabla T) = \nabla.(k\nabla T) \qquad \text{..........................(9)}$$

This involves the consideration of various parameters such as density (ρ), heat capacity (Cp), temperature (T), fluid velocity (→u), and thermal conductivity (k). Notably, it is imperative to acknowledge that the material properties under scrutiny are inherently temperature-dependent, thereby adding a layer of complexity to the modelling process.

In the pursuit of a comprehensive thermal analysis, a modified heat capacity variation with temperature is duly taken into account. This nuanced approach allows for a more accurate representation of the thermal behaviour exhibited by the system under investigation.

$$-n.(-k\nabla T) = q_{in} - h(T - T_0) - \varepsilon\sigma_{Boltz}(T^4 - T_0^4) \qquad \text{..............(10)}$$

Moreover, the energy flux applied to the free surface is a critical component in the overall heat transfer mechanism. Here, factors such as the heat transfer coefficient (h), surface emissivity (ε), Stefan-Boltzmann constant (σ), and the reference temperature (T0) play pivotal roles in shaping the thermal profile of the system.

Furthermore, it is essential to establish robust boundary conditions for the remaining walls within the system. Convective heat fluxes are typically employed to delineate the heat transfer dynamics at these interfaces, thereby ensuring a comprehensive and holistic modelling approach.

In essence, the meticulous consideration of energy balance and the intricate interplay of various parameters within the laser keyhole drilling process underscore the importance of a rigorous and systematic modelling approach. By delving deep into the energy equations and accounting for the nuanced variations in material properties, researchers and engineers can gain valuable insights into the thermal behaviour of metal drilling processes. This not only enhances our understanding of these complex phenomena but also paves the way for the development of more efficient and optimized laser drilling techniques in the realm of material processing and fabrication.

5.2 Heat source modelling

Heat source modelling is a crucial aspect of laser drilling processes on COMSOL Multi-physics. In order to achieve accurate results, it is essential to accurately model the heat source and its interaction with the material being drilled. By accurately representing the heat source, researchers and engineers can predict the temperature distribution, material removal, and overall process efficiency.

One common approach to heat source modelling for laser drilling is to use a Gaussian heat source model. This model assumes that the heat input from the laser beam follows a Gaussian distribution, with the peak intensity at the center of the beam and decreasing towards the edges. By inputting the appropriate parameters such as laser power, spot size, and pulse duration, users can accurately simulate the heat source and predict the resulting temperature distribution.

Another important aspect of heat source modelling is considering the material properties of the work-piece being drilled. Different materials have different thermal conductivity, heat capacity, and melting points, which can significantly impact the heat transfer and material removal process. By accurately incorporating these material properties into the simulation, users can better predict the drilling process and optimize the parameters for maximum efficiency.

In conclusion, heat source modelling is a critical component of laser drilling on COMSOL Multi-physics. By accurately representing the heat source and material properties, researchers and engineers can predict temperature distribution, material removal, and overall process efficiency, ultimately leading to improved results and cost savings.

Chapter 6

2-D AXY-SYMMETRIC CROSS-SECTIONAL MODEL

In the study of laser targeting, the utilization of a 2D axisymmetric model aimed at laser spot targeting, where the laser is focused on a small spot with a diameter ranging from 4mm to 6mm, the choice of meshing technique plays a significant role in ensuring accurate and resource-efficient simulations.

The utilization of a uniform triangular mesh across the entire geometry forms the foundation of the model. The deployment of a uniform triangular mesh augmented by selective fine and coarse meshing represents a robust approach to modelling 2D axisymmetric systems targeted by a laser beam. This tailored meshing strategy allows for a comprehensive analysis of the laser interaction while optimizing computational resources effectively.

Maximum element size	max_e	0.15 mm
Minimum element size	min_e	$3*10^{-4}$ mm
Maximum element growth rate	growR	1.1
Curvature factor	ResCurv	0.2
Resolution of narrow regions	ResNar	1

Table 2: Element size parameters taken for this study

The use of models in scientific research has become increasingly prevalent in recent years, allowing researchers to simulate and predict the behaviour of complex systems with a high degree of accuracy. One such model that is commonly applied in materials science is the carbon black loaded PMMA (polymethyl-methacrylate) model. This model utilizes material properties that are readily available in the literature, supplemented with experimental data, to study the behaviour of this specific material.

The choice to apply this model to a variant of PMMA that is loaded with carbon black is not arbitrary. This particular variant was selected due to its homogeneity, isotropy, and the relatively straightforward characterization of its decomposition from solid to gas phase. These characteristics make it an ideal candidate for studying the behaviour of loaded PMMA and provide a solid foundation for conducting experiments and gathering data.

By utilizing this model, researchers can gain valuable insights into the behaviour of carbon black loaded PMMA, enabling them to better understand its properties, predict its performance under different conditions, and optimize its use in various applications. The combination of material properties from the literature and experimental data allows for a comprehensive analysis of the material, giving researchers a deeper understanding of its characteristics and behaviour.

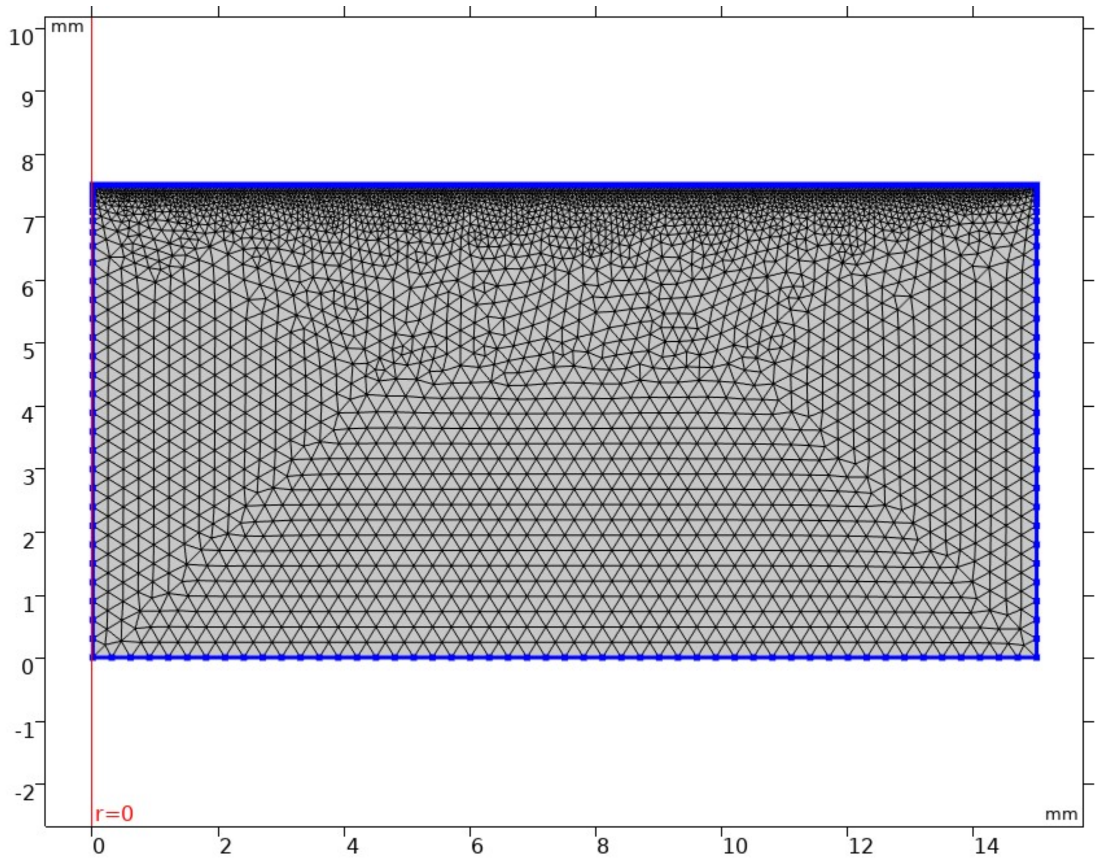

Figure 6: Application of fine meshing around the area where melt penetration was expected for Gaussian Heat Profile

In the field of engineering and scientific research, modelling plays a crucial role in simulating real-world phenomena. The mesh size refers Fig.6. to the resolution of the discretization of the model into elements. A finer mesh size means that the model is divided into smaller elements, which can provide more accurate results but at the cost of increased computational resources and time. On the other hand, a coarser mesh may reduce computational requirements but can lead to inaccuracies in the simulation results. Choosing the appropriate mesh size for a COMSOL model depends on the specific requirements of the simulation. In general, complex geometries or areas with high gradients in the solution variables may require a finer mesh to accurately capture the details of the model. On the other hand, simple geometries or areas with smooth variations may be adequately represented with a coarser mesh.

It is essential to perform mesh refinement studies to determine the optimal mesh size for a given model. This involves running simulations with different mesh sizes and comparing the results to ensure that the chosen mesh provides accurate and reliable results. It is also important to strike a balance between accuracy and computational efficiency, as using an excessively fine mesh may lead to unnecessary computational costs without a significant improvement in the simulation accuracy. In addition, it is crucial to consider the limitations of the computational resources available when selecting the mesh size. Smaller mesh sizes require more memory and processing power, so it is important to optimize the mesh to ensure that the simulation can be performed within the available resources.

6.1 Thermal boundary condition

This essay delves into the significance and implications of thermal boundary conditions, focusing on convection, radiation, and insulation at different boundaries.

At the top and side boundaries of the system, the application of convection boundary conditions plays a crucial role in simulating the heat transfer mechanisms occurring in laser spot processing. Convection involves the transfer of heat through the movement of fluids (either liquids or gases) over a surface. In the case of laser spot processing, convection at the boundaries aids in dissipating the intense thermal energy generated by the laser beam, thus preventing overheating and ensuring the stability of the process.

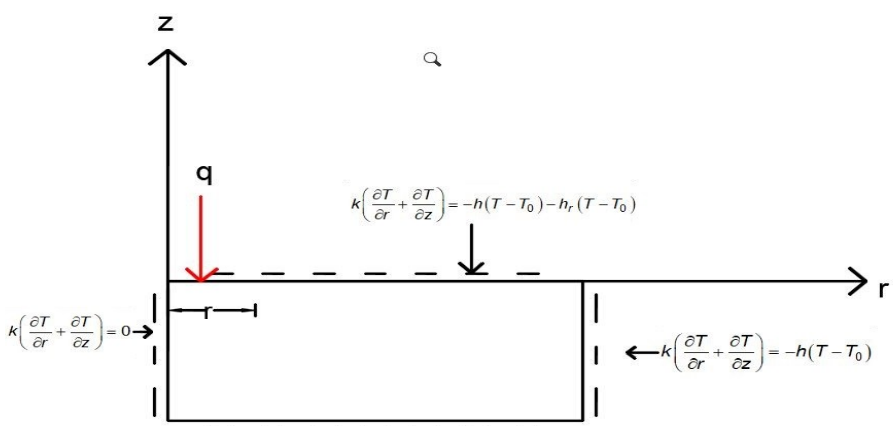

Figure 7 : Thermal Boundary conditions applied on the work-piece

Moreover, at the top boundary specifically, Fig.7 the consideration of radiation due to the high intensity of the laser spot becomes a significant factor. Radiation is characterized by the emission of electromagnetic waves from a surface as a result of its temperature. In laser spot processing, the high-intensity laser beam results in the generation of substantial thermal radiation, which must be accounted for in the thermal model to accurately predict temperature distributions and heat fluxes within the system.

Conversely, the bottom boundary is typically assumed to be insulated in laser spot processing scenarios. An insulated boundary implies that no heat transfer occurs across this boundary, thereby maintaining a constant temperature and minimizing external influences on the thermal profile of the system. This insulation helps in containing the heat within the processing region, facilitating controlled and efficient material processing without undesirable heat losses.

In conclusion, the appropriate selection and implementation of thermal boundary conditions are essential for the effective modelling and analysis of laser spot processing applications. By incorporating convection, radiation, and insulation at the respective boundaries, engineers and researchers can enhance the accuracy and reliability of thermal simulations, leading to optimized process parameters and improved outcomes. As technology advances and computational tools become more sophisticated, the precise characterization of thermal boundary conditions will continue to play a pivotal role in advancing the field of laser spot processing.

Through a comprehensive understanding and application of thermal boundary conditions, the realms of engineering and material processing can harness the power of simulations to drive innovation and efficiency in laser-based technologies.

6.2 Gaussian profile

In the field of laser drilling on PMMA material, Gaussian profile modelling plays a crucial role in accurately predicting and analysing the drilling process. PMMA, also known as poly-methyl methacrylate, is a transparent thermoplastic often used in various applications such as medical devices, automotive parts, and optical components. Laser drilling on PMMA material is a common manufacturing process that requires precise control and optimization to achieve the desired outcomes. Gaussian profile modelling refers to the mathematical representation of the intensity distribution of a laser beam as it interacts with the PMMA material during the drilling process. The Gaussian profile is characterized by a bell-shaped curve, with the highest intensity at the center of the beam and gradually decreasing towards the edges. This modelling approach allows researchers and engineers to simulate the heat distribution, material removal, and overall drilling quality with high accuracy. When using Gaussian profile modelling for laser drilling on PMMA material, several key factors must be considered. These include the laser parameters (such as power, wavelength, and pulse duration), the optical configuration (such as focus position and beam diameter), and the material properties of the PMMA (such as absorption coefficient and thermal conductivity). By integrating these factors into the Gaussian profile model, researchers can predict the drilling depth, diameter, and quality with a high level of precision.

One of the main advantages of Gaussian profile modelling for laser drilling on PMMA material is its ability to optimize the drilling process for specific applications. By adjusting the laser parameters and optical configuration in the model, researchers can determine the most efficient way to achieve the desired drilling results, such as high precision, minimal heat-affected zone, and clean hole edges. This optimization leads to improved productivity, cost savings, and overall quality control in the manufacturing process.

Gaussian profile modelling is an essential tool for laser drilling on PMMA material, providing researchers and engineers with a reliable method to predict and analyse the drilling process. By accurately representing the intensity distribution of the laser beam and considering key factors such as laser parameters, optical configuration, and material properties, Gaussian profile modelling enables optimization of the drilling process for specific applications. This results in improved productivity, cost efficiency, and quality control, making it a valuable asset in the field of laser machining on PMMA material.

6.2.1 Gaussian profile model discussion

The shape of the melt pool following penetration is depicted in Figure 8 with particular parameters encompassing a laser Power(P) of 40 W, a Beam diameter(D) of 6 mm, and a Plate thickness(Th) of 5 mm at Time(t) of 1.325 s . In the figure, the region highlighted in red signifies the portion existing in a liquid state, discerned by the mass fraction of liquid denoted as f (represented as dT(T) in the figure), with temperatures spanning between the melting and boiling points of PMMA material. This visually emphasized red area conveys the anticipated final profile of the drilled hole post the cooling process to room temperature, while the blue segment, signified by 0 in the legend, designates the solid phase. The transition between the liquid and solid phases is evidenced by a multicolour display.

The intricate interplay of various parameters defined by the laser power, beam diameter, plate thickness, and the thermal properties of the material contribute to the formation of the distinct shapes and phases within the melt pool. The significance of understanding the evolution of

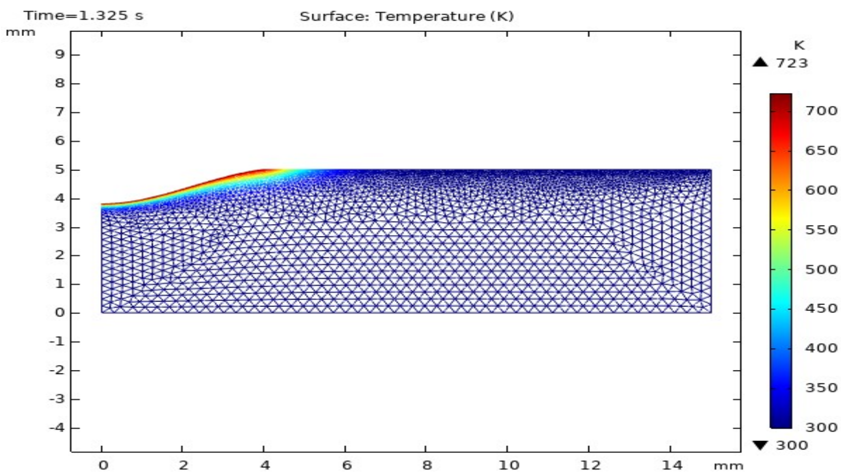

Figure 8: Mass fraction in laser drilling by Gaussian profile at t = 1.325s, P=40 W, D=6 mm 0.9 and Th=5 mm

the melt pool shape lies in its implications for the resulting machined features and the overall quality of the processed material. By meticulously delineating the distinct regions representing the liquid and solid phases, we gain insights into the thermal dynamics and material behaviour during the laser drilling process. This detailed analysis aids in optimizing the process parameters to achieve desired outcomes in terms of hole geometry, surface finish, and material properties.

The delineation between the liquid and solid phases within the melt pool is not only a visual representation of the material state but also a window into the complex thermal interactions taking place during laser drilling. The transformation from molten to solid state governs the final structure and properties of the drilled hole, thus underscoring the significance of monitoring and controlling the melt pool shape. This understanding serves as a foundational element in the realm of laser drilling, enabling researchers and practitioners to advance the precision, efficiency, and reliability of the manufacturing processes involving laser-machined components.

In the course of the experimental procedure, the Poly(methyl methacrylate) (PMMA) material is subjected to the heating effects induced by a pulsed Neodymium-doped Yttrium Aluminium Garnet (Nd:YAG) laser beam, which operates with a periodic on and off cycle of

50 milliseconds. The cumulative exposure time of the laser beam stands at 2 seconds. Throughout the heating phase, the directional alteration in velocity is illustrated in figure 23

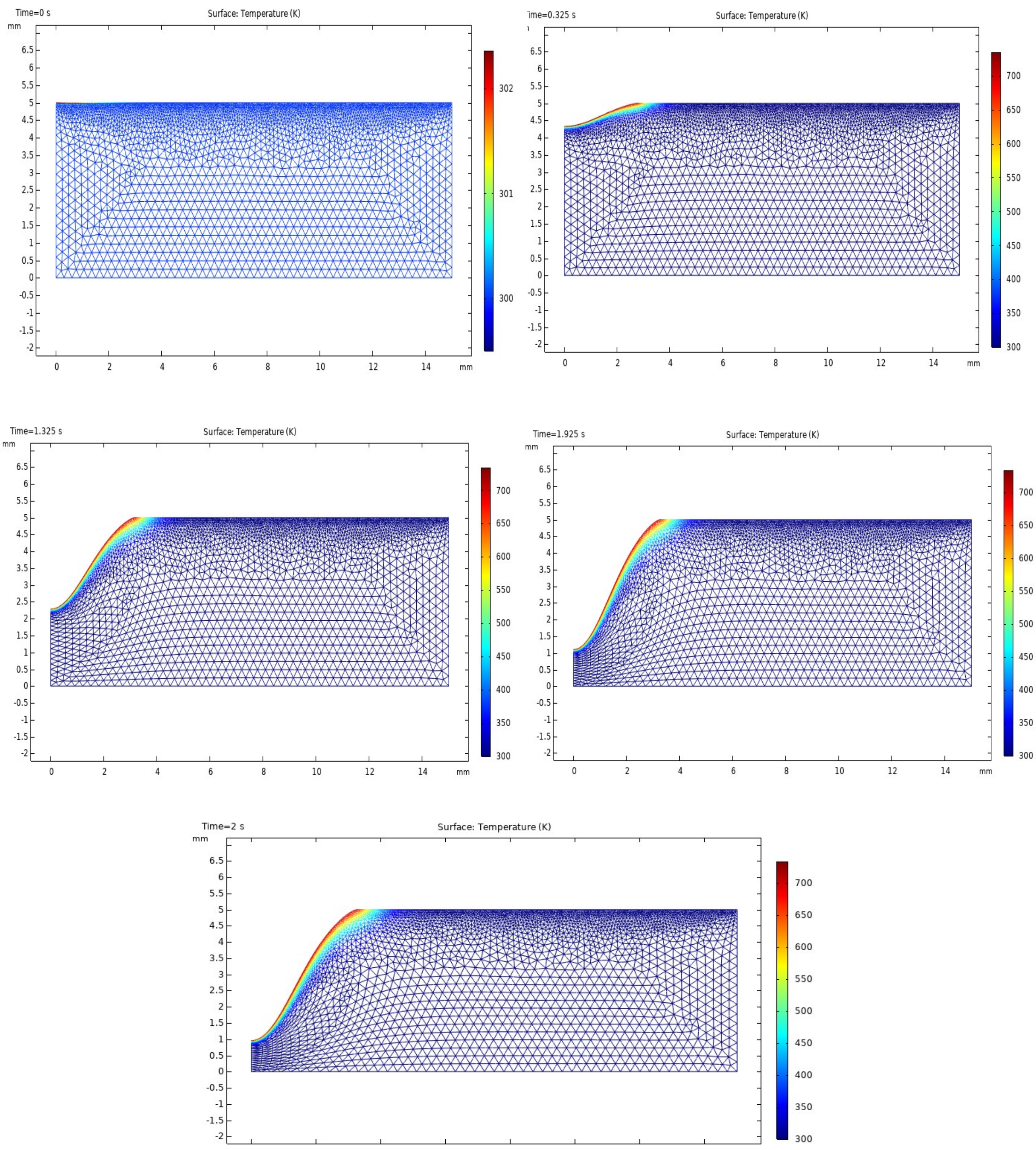

Figure 9: Temperature distribution in laser drilling by Gaussian profile at t = 0.0 s, 0.325 s, 1.325 s, 1.925 s, 2 s respectively, P = 40 W, D = 4 mm and Th = 5 mm.

In conclusion, the visualization of the melt pool shape post-penetration in Figure 8 elucidates the intricate dynamics of material phase transitions and thermal behaviour during laser drilling. By decoding the information embedded in the distinct regions representing liquid and solid phases, researchers and engineers can fine-tune process parameters and enhance the quality and consistency of laser-drilled features. This analytical approach not only enhances our comprehension of laser-machining processes but also paves the way for advancements in precision manufacturing and material processing techniques.

Chapter 7

NUMERICAL RESULTS AND DISCUSSION

7.1 INTRODUCTION

In the field of material processing, laser drilling is a widely used technique for creating precise holes in various materials. One such material is PMMA (Polymethyl Methacrylate), which is commonly used in industries for its transparency, strength, and weather resistance. In a recent study, the response from numerical simulations for laser drilling of PMMA material at the end of 2 seconds was collected and analysed. The study focused on determining the effects of different process parameters on the width and depth of the hole created during laser drilling. These process parameters, along with their symbols, units, and low actual and high actual values, were carefully selected and presented in Table 3. This table provided a comprehensive overview of the variables considered and their respective ranges in the numerical simulations.

Parameters	Symbol	Unit	Low actual	High actual
Laser Power	P	W	15	40
Beam diameter	d	mm	4	6
Plate Thickness	t	mm	5	10

Table 3 : Process parameters and their units and limits

7.2 DOE in numerical investigation

The numerical simulations are conducted based on a specific design layout and it is listed in Table 4. The DOE is made with Design-Expert® software. Central composite design (CCD) based RSM technique is used to prepare the DOE. Easy to establish a nonlinear relationship between input factors and output response, requirement of fewer experiments than other designs to estimate the main effects, the interactions, and the curvature of the response surface make CCD an obvious choice for the selection of this work. Alpha (α) value of CCD is an important factor which is the calculated distance of individual axial point from the center point. α value of this work is 1.2 and laser power, beam diameter, and plate thickness are selected input factors.

Sl No	Laser Power	Beam diameter	Plate Thickness	Hole Depth	Hole Width
	A:P	B:D	C:Th	R1	R2
Unit	W	mm	mm	Mm	mm
1	40	6	5	2.8284	8.2592
2	27.5	5	7.5	1.7957	6.7402
3	15	4	10	1.4919	5.2558
4	15	4	5	1.4897	5.225
5	27.5	5	7.5	1.7957	6.7402
6	27.5	5.2	7.5	1.6617	6.9976
7	40	4	10	4.0471	6.4496
8	40	6	10	1.8298	8.2298
9	40	4	5	4.04994	6.4326
10	15	6	5	0.582	6.0926
11	15	6	10	0.5797	6.0932
12	27.5	5	7	1.7916	6.8058
13	27.5	4.8	7.5	1.9484	6.6694
14	27.5	5	7.5	1.7957	6.7402
15	27.5	5	7.5	1.7957	6.7402
16	30	5	7.5	1.9628	6.9122
17	27.5	5	8	1.7978	6.7194
18	27.5	5	7.5	1.7957	6.7402
19	25	5	7.5	1.6374	6.6526
20	27.5	5	7.5	1.7957	6.7402

Table 4: Design layout and numerically calculated response

Overall, the collection and analysis of numerical simulation data for laser drilling of PMMA material have provided valuable information for researchers and practitioners in the field. By understanding the impact of different process parameters on hole characteristics, it is possible to make informed decisions and improvements in material processing techniques. This study serves as a valuable contribution to the ongoing research and development in laser drilling technology and its applications in various industries.

7.3 Numerical results for Hole Depth (mm)

The responses were observed for twenty different combinations of the process parameters, allowing for a detailed analysis of the relationship between the input variables and the hole characteristics. Through this study, valuable insights were gained regarding the optimal process conditions for laser drilling of PMMA material. By systematically varying the process parameters and analysing the resulting responses, researchers were able to identify key factors influencing the width and depth of the drilled holes. This information can be used to optimize the laser drilling process, improve hole quality, and enhance the overall efficiency of material processing operations. The numerical results for hole depth is presented in table 4.

7.3.1 Regression equation

The mathematical model for the maximum depth of the hole as a function of process parameters has been successfully achieved using the Design Expert Software. This advanced software tool has enabled researchers to accurately predict the relationship between various process parameters and the resulting maximum depth of the hole. By using regression analysis, researchers can quantify the effects of these factors and optimize the drilling process to achieve the desired hole depth. This equation serves as a valuable tool in laser drilling research and development, allowing engineers to predict hole depths and make informed decisions about process parameters. With continuous refinement and validation, the regression equation for hole depth laser drilling can significantly improve the efficiency and effectiveness of laser drilling operations. The regression model for the hole depth is presented in equation number 5.

The Regression Equation is –

$$\text{Hole Depth} = 4.28993 + 0.158430\,P - 2.16797\,D + 0.372410\,Th - 0.016189\,P * D - 0.004005\,P * Th - 0.050013\,D * Th + 0.000699\,P^2 + 0.233034\,D^2 - 0.004114\,Th^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (12)$$

7.3.2 ANOVA table discussion for hole depth

The model F-value of 119.46 serves as a crucial indicator of the significance of the model, suggesting that there is a 0% probability that such a large 'model F-value' could arise merely as a result of noise. The ANOVA table pertaining to the quadratic model offers further insight, accompanied by other measures of adequacy as detailed in Table 5. Typically, the R^2 value ranges from 0 to 1, with higher values indicating a stronger predictive capability. In the context of the predicted regression model, the R^2 value stands impressively at 0.9908, a figure in close proximity to 1. This near-perfect R^2 value underscores the model's robust predictive capacity.

Source	Degree of freedom	Sum of Squares	Mean Square	F-value	p-value	Remarks
Model	9	13.99	1.55	119.46	< 0.0001	significant
A-P	1	9.32	9.32	715.95	< 0.0001	
B-D	1	3.50	3.50	268.74	< 0.0001	
C-Th	1	0.1238	0.1238	9.51	0.0115	
AB	1	0.3276	0.3276	25.17	0.0005	
AC	1	0.1253	0.1253	9.63	0.0112	
BC	1	0.1251	0.1251	9.61	0.0113	
A^2	1	0.0001	0.0001	0.0044	0.9484	
B^2	1	0.0003	0.0003	0.0200	0.8903	
C^2	1	3.174E-06	3.174E-06	0.0002	0.9878	
Residual	10	0.1302	0.0130			
Lack of Fit	5	0.1302	0.0260			
Pure Error	5	0.0000	0.0000			
Cor Total	19	14.12				
R^2 = 0.9908			**Adjusted R^2** = 0.9825			

Table 5: ANOVA for response surface quadratic model of maximum depth of hole & Model Summary

The statistical analysis conducted reveals that model terms with associated p-values less than 0.05 are deemed significant. According to the ANOVA results, the impact of laser power (P), beam diameter (D), plate thickness (Th), square, 2-way interaction, D^2, P×D, D*Th, P*Th are identified as the most influential model terms for determining the maximum width of the plate. Conversely, the remaining model terms do not exhibit statistical significance in this study.

7.3.3 Effect of process parameters on Hole Depth

In the realm of material machining, understanding the intricate relationship between various process parameters and their effects on the final outcome is crucial for achieving optimal results. Through the utilization of response surface models, researchers have been able to delve deep into the effects of these parameters, paving the way for enhanced precision and efficiency in machining processes. The core focus of this study lies in the investigation of the impact of process variables such as laser power, plate thickness, and beam diameter on the maximum hole depth achieved during machining operations. By analysing the 3-D surface plots & contour plots generated through these models, a comprehensive understanding of how these parameters interact and influence the final outcome can be attained.

Surface plots are essential diagrams in visualizing three-dimensional data. While scatter plots display individual data points, surface plots illustrate the relationship between a dependent variable (Y) and two independent variables (X and Z). These plots help in understanding the functional relationships between variables (Power, Beam Diameter and Plate Thickness) & are often used in conjunction with contour plots. Contour plots provide a valuable tool for visually representing how input process parameters impact a response. By plotting constant Z slices, or contours, in a two-dimensional format, these plots allow for easy visualization of a three-dimensional surface. In the context of a contour plot focusing on the parameters of Power, Beam Diameter, and Plate Thickness, colours are used to indicate areas of increase and decrease in relation to the objective function. This graphical representation offers a clear and concise way to understand the effects of input process parameters on the overall response.

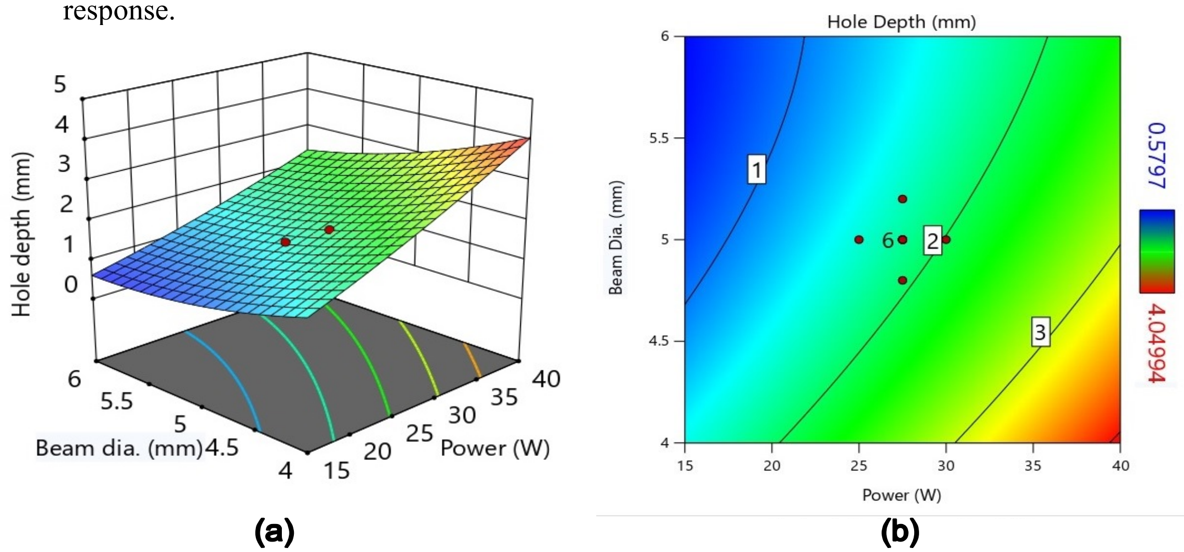

Figure 10: (a) 3-D Surface plot (b) Contour plot for the effect of laser power and beam dia. on hole depth.(Plate thickness = 7.5 mm)

Figure 10 (a) on 3-D Surface plots & (b) shows the effect of the interaction between laser power and beam diameter. From the plot it is observed that the depth of the hole increases as the laser power increases. This is likely because the laser beam has more energy to vaporize the material as the power increases. The effect of beam diameter on hole depth is more complex. At a constant laser power, the depth of the hole generally decreases as the beam diameter increases. This is likely because a larger diameter beam spreads out the laser's energy over a larger area, reducing the power density of the beam and its ability to penetrate deeply.

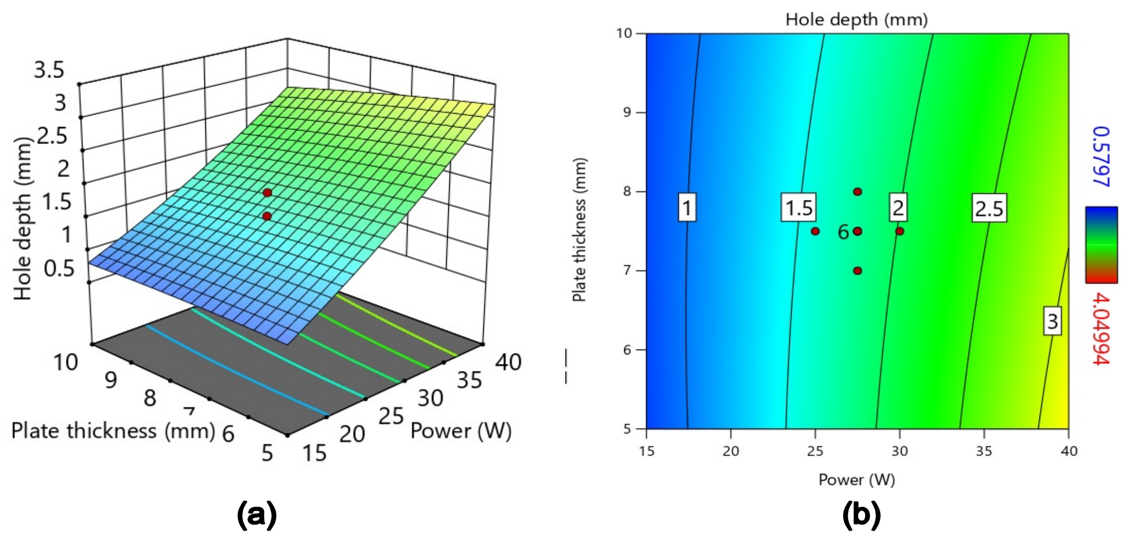

Figure 11: (a) 3-D Surface plot & (b) Contour plot for the effect of laser power and plate thickness on hole depth.(Beam dia. = 5mm)

Figure 11 (a) on 3-D Surface plots & (b) shows the effect of the interaction between laser power and plate thickness. From the plot it is observed that the depth of the hole increases as the plate thickness increases. The effect of laser power on hole depth is also evident from the graph. As the power of the laser increases, the depth of the hole also increases. This is likely because the laser beam has more energy to vaporize the material as the power increases.

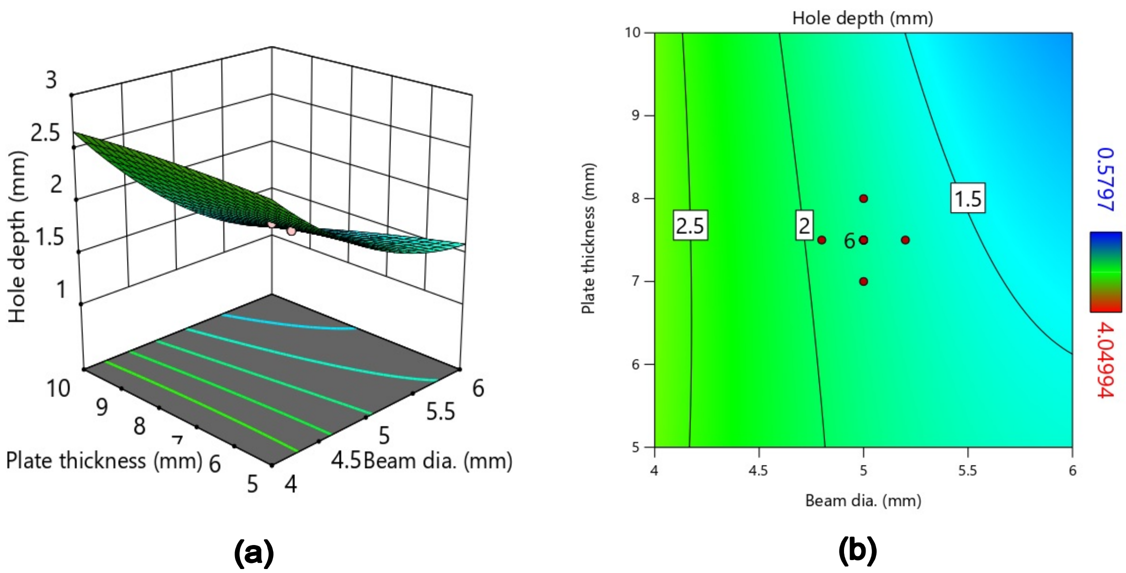

Figure 12: (a) 3D Surface plot & (b) Contour plot for effect of beam dia. and plate thickness on hole depth. (Power = 27.5 W)

Figure 12 (a) on 3-D Surface plots & (b) shows the effect of interaction between beam diameter and plate thickness. From the plot it is observed that the depth of the hole increases as the plate thickness increases. This is likely because the laser beam has more material to interact with as the plate thickness increases. The effect of beam diameter on hole depth is more complex. At a constant plate thickness, the depth of the hole generally decreases as the beam diameter increases. This is likely because a larger diameter beam spreads out the laser's energy over a larger area, reducing the power density of the beam and its ability to penetrate deeply.

7.4 Numerical results for Hole Dia.

Drill hole diameter is also an important factor regarding hole geometry. The numerical results for hole dia.is listed in table 4. This data has the potential to enhance the laser drilling procedure, elevate the quality of holes, and boost the efficiency of material processing tasks.

7.4.1 Regression equation

The mathematical model for the maximum dia. of the hole as a function of process parameters has been successfully achieved using the Design Expert Software. This advanced software tool has enabled researchers to accurately predict the relationship between various process parameters and the resulting maximum dia. of the hole. By using regression analysis, researchers can quantify the effects of these factors and optimize the drilling process to achieve the desired hole dia. This equation serves as a valuable tool in laser drilling research and development, allowing engineers to predict hole dia. and make informed decisions about process parameters. With continuous refinement and validation, the regression equation for hole dia. laser drilling can significantly improve the efficiency and effectiveness of laser drilling operations. The regression model for the hole dia. is presented in equation number 6.

The Regression Equation is

$$\text{Hole Dia.} = 17.98118 + 0.095801\,P - 9.11850\,D + 2.04851\,Th + 0.019018\,P*D - 0.000175\,P*Th - 0.003830\,D*Th - 0.002231\,P^2 + 0.928975\,D^2 - 0.134964\,Th^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots(13)$$

7.4.2 ANOVA table discussion

The model F-value of 618.87 indicates that the model is highly significant, with a 0% chance that such a value could occur due to random noise. The ANOVA table for the quadratic model, along with other adequacy measures, is presented in Table 6. Typically, the R2 value ranges from 0 to 1, with a value of 0.9982 indicating a regression model's strong predictive capability. Moreover, with a p-value of less than 0.05, the model terms are deemed significant. The ANOVA results highlight the importance of laser power (P), beam diameter (D), plate thickness (Th), as well as the 2-way interactions for influencing the maximum width of the plate. Conversely, the other model terms are found to be non-significant.

Source	Degree of freedom	Sum of Squares	Mean Square	F-value	p-value	Remarks
Model	9	10.01	1.11	616.87	< 0.0001	significant
A-P	1	5.65	5.65	3132.04	< 0.0001	
B-D	1	3.58	3.58	1983.96	< 0.0001	
C-Th	1	3.661E-07	3.661E-07	0.0002	0.9889	
AB	1	0.4521	0.4521	250.63	< 0.0001	
AC	1	0.0002	0.0002	0.1329	0.7230	
BC	1	0.0007	0.0007	0.4066	0.5380	
A^2	1	0.0006	0.0006	0.3232	0.5822	
B^2	1	0.0041	0.0041	2.30	0.1606	
C^2	1	0.0034	0.0034	1.89	0.1989	
Residual	10	0.0180	0.0018			
Lack of Fit	5	0.0180	0.0036			
Pure Error	5	0.0000	0.0000			
Cor Total	19	10.03				
R^2 = 0.9982				**Adjusted R^2** = 0.9966		

Table 6: ANOVA for response surface quadratic model of maximum dia of hole & Model Summary

7.4.3 Effect of process parameters on Hole Dia.

The study delves into the analysis of parameters influencing the response through a developed response surface model. Gaining insight into the intricate relationship between process variables like laser power, pulse on time, and their impact on maximum hole dia. is crucial for optimizing outcomes in various applications.

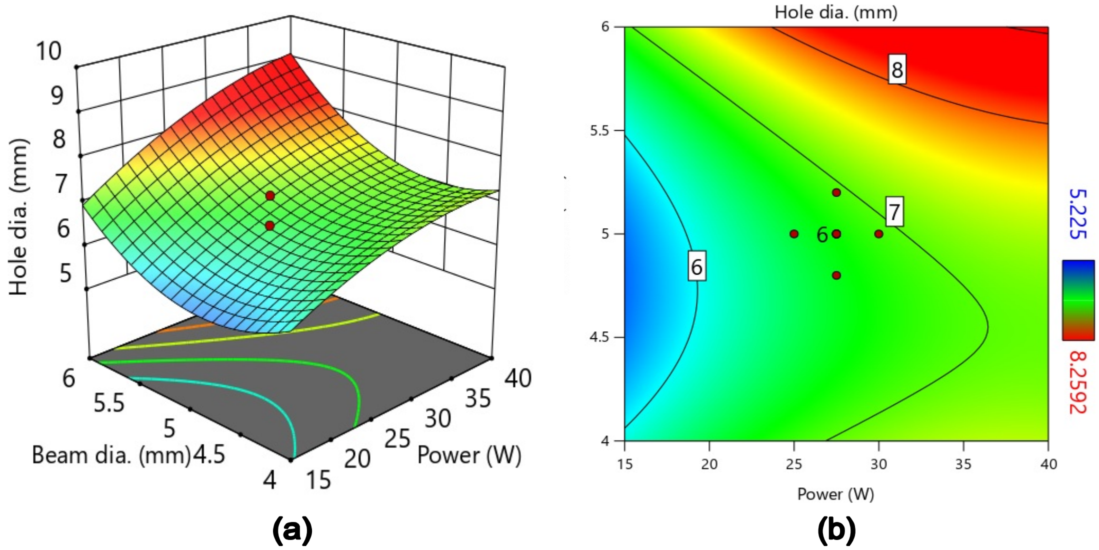

Figure 13: (a) 3-D Surface plot & (b) Contour plot for the effect of laser power and beam dia. on hole dia. (Plate thickness = 7.5 mm)

Figure 13 (a) on 3-D surface plots & (b) shows the effect of interaction between laser power and beam diameter. From the plot it is observed that the diameter of the hole increases as the laser power increases, for. This is likely because the laser beam has more energy to vaporize the material as the power increases. At a constant plate thickness, the diameter of the hole generally increases as the beam diameter increases. This is likely because a larger diameter beam spreads out the laser's energy over a larger area, reducing the power density of the beam and its ability to penetrate widely.

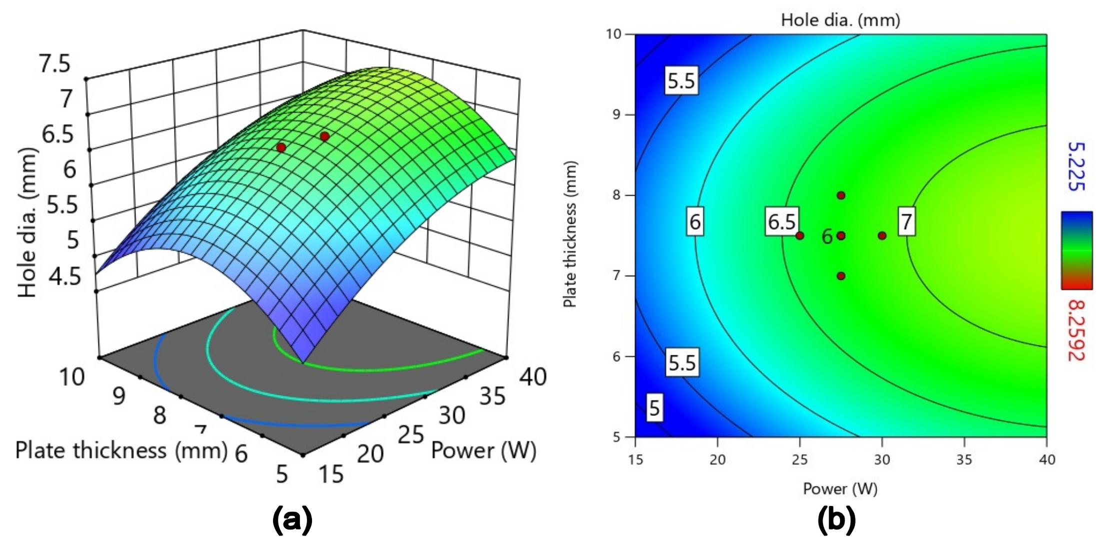

Figure 14: (a) 3-D Surface plot & (b) Contour plot for the effect of laser power and plate thickness on hole dia. (Beam dia. = 5 mm)

Figure 14 (a) on 3-D Surface plots & (b) shows the effect of interaction between laser power and plate thickness. From the plot it is observed that the diameter of the hole increases as the laser power increases. This is likely because the laser beam has more energy to vaporize the material as the power increases. The effect of plate thickness on hole diameter is less clear from this graph. It appears that at lower laser powers, the hole diameter increases slightly as the plate thickness increases. At higher laser powers, there seems to be little to no effect of plate thickness on hole diameter.

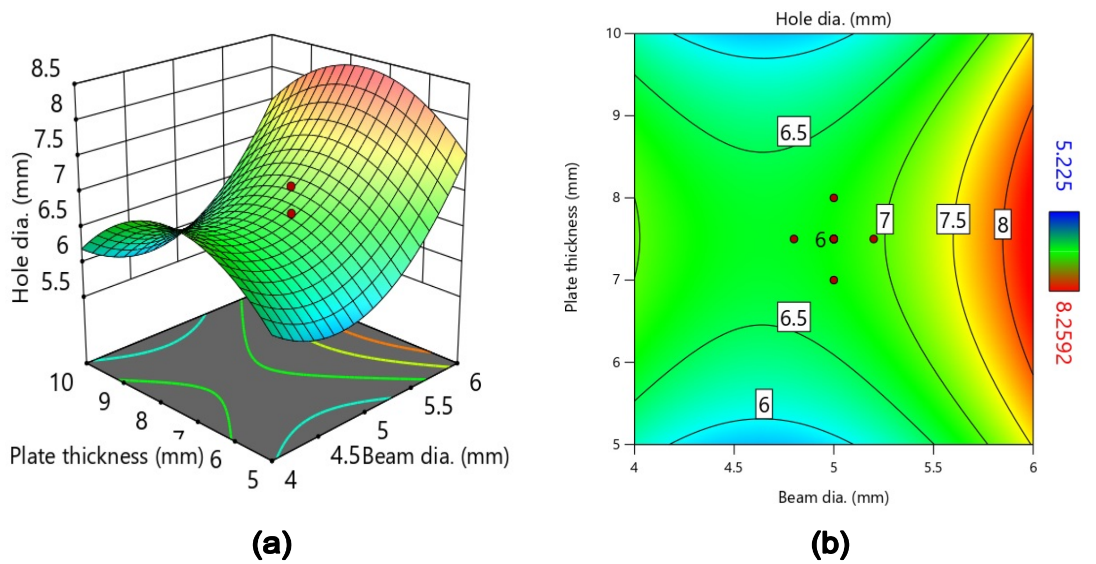

Figure 15: (a) 3-D Surface plot & (b) Contour plot for the effect of beam dia. and plate thickness on hole dia. (Power = 27.5W)

Figure 15 (a) on 3-D Surface plots & (b) shows the effect of interaction between laser power and plate thickness. From the plot it is observed that the hole increases as the plate thickness increases. This is likely because the laser beam has more material to interact with as the plate thickness increases. The effect of beam diameter on hole diameter is more complex. At a constant plate thickness, the diameter of the hole generally increases as the beam diameter increases. This is likely because a larger diameter beam vaporizes a larger area of material.

In conclusion, the meticulous examination of these interactions and their effects on the response surface not only enhances our understanding of the underlying dynamics but also lays the groundwork for informed decision-making and optimization strategies in relevant processes and systems.

Chapter 8

CONCLUSION AND FUTURE SCOPE OF WORK

8.1 CONCLUSION

The comprehensive investigation of laser drilling on PMMA material presented in this study provides valuable insights into the intricate dynamics governing the process. Through meticulous analysis of various parameters such as laser power, plate thickness, and beam diameter, the study elucidates the profound impact these factors have on the characteristics of drilled holes, including their depth and diameter.

One of the key findings is the significant role of laser power in determining hole depth and diameter. As the laser power increases, there is a corresponding increase in the energy available to vaporize the material, resulting in deeper and larger holes. This relationship highlights the importance of optimizing laser power to achieve the desired drilling outcomes.

Furthermore, the study reveals the complex interplay between beam diameter and hole characteristics. At a constant laser power, an increase in beam diameter generally leads to a decrease in hole depth. This phenomenon can be attributed to the distribution of laser energy over a larger area, which reduces the power density and thus the material's ability to be deeply penetrated. This finding underscores the need for precise control of beam diameter to fine-tune the drilling process for specific applications.

The effect of plate thickness on hole diameter is also examined, showing that at lower laser powers, the hole diameter increases slightly with plate thickness, whereas at higher powers, the thickness has negligible effect. This nuanced understanding of the relationship between plate thickness and hole characteristics allows for better customization of the drilling process based on material properties.

Moreover, the study's use of advanced modelling techniques, such as 3-D surface plots and contour plots, provides a robust framework for visualizing the effects of various parameters on the drilling process. These visual tools facilitate a deeper understanding of the functional relationships between the input variables and the resulting hole characteristics, enabling more informed decision-making and optimization strategies.

In conclusion, this research enhances our understanding of laser drilling processes and offers practical insights for improving precision and efficiency in material machining. By integrating computational simulations with experimental studies, the findings pave the way for advancements in laser machining technology, ultimately contributing to more refined and effective manufacturing processes.

8.2 FUTURE SCOPE OF WORK

In my upcoming computational research, I plan to delve into several key areas that will contribute to a deeper understanding of laser drilling processes. One of the main focuses will be on the assist gas used during drilling and how its flow impacts the overall process. It will be crucial to study the path of the assist gas as it impinges on the surface and investigate how varying gas pressure affects the drilling quality of specimens.

In addition to numerical investigations, I intend to conduct experimental studies to complement my computational research. Thermo-graphic studies using infrared cameras will provide valuable insights into the temperature distribution during drilling. Additionally, using sensors to monitor acoustic noise and correlate it with different process parameters will help establish a relationship between process conditions and acoustic emission.

Overall, my future research will tackle various aspects of laser drilling, combining computational simulations with experimental studies to gain a comprehensive understanding of the intricate processes involved. Through this multi-faceted approach, I aim to make significant contributions to the field of laser machining technology.

Laser drilling has become a widely used technique in various industries such as aerospace, automotive, and electronics manufacturing due to its precision and efficiency. However, there are still challenges and limitations that need to be addressed in order to further optimize the process and improve drilling quality. By focusing on the assist gas flow, interactive forces, acoustic emission, and material properties during laser drilling, my research aims to provide valuable insights that can lead to advancements in the field.

One of the key areas of my research will be the study of assist gas flow and its impact on the drilling process. The assist gas plays a crucial role in facilitating the removal of molten material from the drill hole, as well as in controlling the heat affected zone. By investigating the path of the assist gas as it interacts with the laser beam and the work-piece, I hope to optimize the gas flow parameters to improve drilling accuracy and efficiency.

Furthermore, studying acoustic emission during laser drilling can provide valuable information about the material removal process and the formation of defects such as cracks and voids. By monitoring and analysing the acoustic signals generated during drilling, it is possible to identify potential issues and optimize process parameters to improve drilling quality.

In addition to these simulations and analyses, experimental studies will be conducted to validate the findings and ensure the reliability of the research results. Thermo-graphic imaging and acoustic noise monitoring will provide real-time data that can be used to correlate with computational models and verify the accuracy of the predictions.

Overall, the comprehensive approach of my research aims to address the complex challenges and limitations of laser drilling by integrating computational simulations with experimental studies. This research has the potential to have a significant impact on various industries by enhancing drilling precision, efficiency, and quality, ultimately leading to advancements in laser machining technology.

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