

## **ANALYSIS OF WELD POOL CHARACTERISTICS GENERATED USING ND: YAG LASER**

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### **Abstract**

Laser welding is a widely used advanced manufacturing process due to its high precision, efficiency, and ability to produce high-quality joints. Among various laser systems, the Nd:YAG laser is particularly significant because of its high energy density and flexibility in material processing. This study presents a detailed analysis of weld pool characteristics generated using a Nd:YAG laser system, with a focus on the influence of key process parameters such as laser beam diameter, laser power, and scanning velocity.

A numerical approach based on the Finite Difference Method (FDM) is employed to simulate transient heat transfer within a metal plate. The developed model predicts temperature distribution and weld pool formation under varying operating conditions. The simulation results indicate that a reduction in laser beam diameter increases energy concentration, resulting in deeper weld penetration. In contrast, an increase in scanning velocity reduces the interaction time between the laser beam and the material, thereby decreasing penetration depth. Furthermore, higher laser power significantly increases the temperature within the weld zone, leading to enhanced melting and deeper weld pool formation.

The study also highlights that material absorption increases after reaching the melting point, causing a sudden rise in penetration depth. These findings provide valuable insights into the relationship between process parameters and weld quality. The results can be effectively utilized to optimize laser welding processes, improve performance, minimize defects, and enhance overall industrial productivity.

## **I. Introduction**

Laser welding is a highly advanced manufacturing process widely utilized in industries such as automotive, aerospace, and precision engineering due to its superior accuracy, high energy density, and ability to produce strong, defect-free joints. Among the various types of laser systems, the Nd:YAG (Neodymium-doped Yttrium Aluminum Garnet) laser holds particular importance because of its capability for fiber-optic delivery, deep penetration welding, and adaptability to different processing conditions. The present study focuses on a comprehensive analysis of weld pool characteristics generated using a Nd:YAG laser system, with emphasis on understanding the influence of key process parameters on weld quality and thermal behavior.

The primary objective of this research is to investigate how variations in laser beam diameter, laser power, and scanning velocity affect weld penetration depth, temperature distribution, and melt pool geometry. To achieve this, a numerical simulation approach based on the Finite Difference Method (FDM) is employed to model transient heat transfer within a metallic workpiece. The computational domain is discretized into a structured grid, and the governing heat conduction equations are solved under appropriate boundary conditions, including convective heat loss and temperature-dependent material properties. This method enables accurate prediction of thermal fields and provides detailed insight into the evolution of the weld pool over time.

The simulation results demonstrate clear relationships between the process parameters and weld characteristics. It is observed that a decrease in laser beam diameter results in a higher concentration of energy, leading to deeper and more efficient weld penetration. On the other hand, an increase in scanning velocity reduces the interaction time between the laser beam and the material surface, thereby decreasing heat input and limiting penetration depth. Furthermore, increasing the laser power significantly raises the temperature within the weld zone, promoting enhanced melting and deeper weld pool formation.

An important finding of this study is the nonlinear behavior of material absorption during phase transformation. As the material reaches its melting point, its absorption characteristics change, resulting in a sudden increase in penetration depth. This phenomenon highlights the importance of incorporating temperature-dependent properties in numerical models for more accurate predictions.

Overall, the results of this study provide valuable insights into the thermal and physical behavior of weld pools under varying operating conditions. The findings can be effectively utilized to optimize laser welding parameters, improve weld quality, reduce defects, and enhance overall process efficiency. Additionally, the numerical modeling approach presented in this work offers a cost-effective and reliable alternative to extensive experimental trials, making it highly beneficial for industrial applications and future research in laser material processing.

## II. Methodology

The present study employs a numerical approach based on the Finite Difference Method (FDM) to analyze transient heat conduction in a two-dimensional metallic domain subjected to laser heating. The methodology is designed to simulate the thermal behavior of the weld pool and to predict temperature distribution under varying process parameters.

### A. Governing Equation

The heat transfer within the metal plate is governed by the two-dimensional transient heat conduction equation:

$$\rho c \frac{\partial T}{\partial t} = k \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) + Q$$

where  $T$  is temperature,  $t$  is time,  $k$  is thermal conductivity,  $\rho$  is density,  $c$  is specific heat, and  $Q$  represents internal heat generation due to the laser source. The equation accounts for transient heat flow and spatial temperature variations within the domain.

## B. Discretization Using Finite Difference Method

The computational domain (metal plate) is discretized into a structured grid consisting of equally spaced nodes along both spatial directions. The derivatives in the governing equation are approximated using finite difference formulations.

An explicit time-marching scheme is adopted, where the temperature at each node for the next time step is calculated using the current temperature values of neighboring nodes. This approach enables step-by-step tracking of temperature evolution within the weld region.

## C. Boundary Conditions

To accurately represent physical conditions, appropriate boundary conditions are applied:

### 1. Convective Boundary Condition

Heat loss from the surface to the surrounding environment is modeled using Newton's law of cooling:

$$-k \frac{\partial T}{\partial n} = h(T - T_{\infty})$$

where  $h$  is the convective heat transfer coefficient and  $T_{\infty}$  is ambient temperature.

### 2. Insulated Boundary Condition

Certain boundaries are assumed to be adiabatic, meaning no heat transfer occurs across them.

### 3. Initial Condition

The entire plate is assumed to be at a uniform initial temperature before laser irradiation begins.

## D. Nodal Classification and Equations

Different finite difference equations are applied based on the location of nodes within the grid:

- **Interior Nodes**

These nodes are surrounded by neighboring nodes on all sides. The temperature update is based on heat conduction in both spatial directions.

- **Boundary Nodes**

These nodes are located along the edges of the domain and incorporate convective or insulated boundary conditions into their governing equations.

- **Corner Nodes**

Special treatment is required for corner nodes since they are influenced by boundary conditions in two directions simultaneously.

This classification ensures accurate modeling of heat transfer across the entire domain.

### **E. Stability Criterion**

The numerical solution is conditionally stable and requires satisfaction of the Fourier number criterion:

$$Fo = \frac{\alpha \Delta t}{\Delta x^2} \leq \frac{1}{4}$$

where  $\alpha = \frac{k}{\rho c}$  is thermal diffusivity. The time step ( $\Delta t$ ) and grid spacing ( $\Delta x, \Delta y$ ) are selected carefully to ensure numerical stability and convergence of the solution.

### **F. Simulation Procedure**

The simulation is carried out through the following steps:

1. Initialization of temperature field
2. Application of boundary conditions
3. Iterative computation of nodal temperatures using FDM equations
4. Updating temperature distribution for each time step
5. Monitoring weld pool formation and penetration depth

### **G. Model Assumptions**

To simplify the analysis, the following assumptions are made:

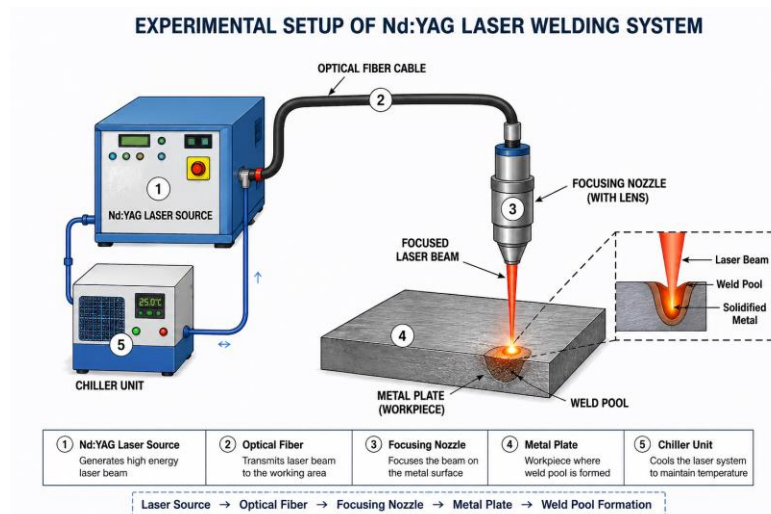
- Material properties are temperature-dependent
- Heat transfer is two-dimensional
- Radiation effects are neglected
- The laser heat source is uniformly distributed over the beam area

### III. Experimental Setup

The experimental setup is designed to study how a weld pool is formed using a Nd:YAG laser. It includes several important components that work together to generate, control, and apply the laser beam on a metal surface.

#### Main Components of the Setup

- 1. Nd:YAG Laser Source**  
This is the main device that generates the laser beam. It produces a high-energy light beam which is used for welding. The laser has very high power and can easily melt metal.
- 2. Optical Fiber**  
The laser beam is not directly applied to the metal. Instead, it is first passed through an optical fiber. This fiber acts like a path or cable that safely carries the laser beam from the source to the working area. It also allows flexibility in positioning.
- 3. Focusing Nozzle (with Lens)**  
At the end of the optical fiber, a nozzle with a lens is attached. The lens focuses the laser beam into a very small spot. This increases the energy concentration, which is necessary to melt the metal surface and create a weld pool.
- 4. Metal Plate (Workpiece)**  
This is the material on which the laser beam is applied. When the focused laser beam hits the metal surface, it heats up very quickly and starts melting, forming a small molten region called the weld pool.
- 5. Chiller Unit**  
The laser system generates a lot of heat during operation. The chiller unit is used to cool down the laser equipment and maintain a stable temperature. This prevents overheating and ensures proper functioning of the system.



### **Working Process**

- First, the laser system is switched on using the power supply.
- The Nd:YAG laser generates a high-energy beam inside the laser cavity.
- This beam is transmitted through the optical fiber to the nozzle.
- The focusing lens in the nozzle concentrates the beam on a small area of the metal plate.
- Due to high energy concentration, the metal surface heats up rapidly and melts.
- This melted region forms the weld pool.
- At the same time, the chiller unit removes excess heat from the system to keep it stable.

### **IV. Results and Discussion**

The numerical simulation based on the Finite Difference Method (FDM) was carried out to analyze the influence of key process parameters on weld pool characteristics. The results are presented in three cases to understand the effects of beam diameter, laser scanning velocity, and laser power on weld penetration and thermal behavior.

#### Case 1: Effect of Beam Diameter

In this case, the laser beam diameter is varied while keeping laser power and scanning velocity constant. It is observed that decreasing the beam diameter increases the energy concentration at the focal point. A smaller beam diameter results in higher heat intensity per unit area, causing the material to absorb more heat in a localized region. This leads to faster melting and deeper weld penetration. The temperature distribution becomes highly concentrated, forming a narrow and deep weld pool.

#### Discussion:

Reducing the beam diameter improves laser-material interaction by focusing energy into a smaller area. While this enhances penetration efficiency, it may also increase the risk of excessive melting if not properly controlled.

#### Case 2: Effect of Laser Scanning Velocity

Here, the laser scanning velocity is varied while keeping beam diameter and power constant. Increasing the scanning velocity reduces the interaction time between the laser beam and the material. As a result, the heat input per unit length decreases, leading to a lower temperature rise. Consequently, the weld pool becomes shallower and less defined. At very high velocities, incomplete melting or weak joints may occur.

Discussion:

Laser velocity plays a crucial role in controlling heat input. Higher velocity reduces thermal accumulation, while lower velocity increases penetration. Therefore, selecting an optimal velocity is essential for achieving good weld quality.

Case 3: Effect of Laser Power

In this case, laser power is varied while other parameters are kept constant. Increasing laser power significantly raises the temperature in the weld zone. Higher energy input results in greater melting and deeper weld pool formation. The weld pool also becomes wider as power increases. However, excessively high power may lead to overheating and defects such as porosity.

Discussion:

Laser power directly affects the amount of heat delivered to the material. Proper control is necessary to achieve the desired weld depth without damaging the material.

Overall Observation

A sudden increase in weld penetration is observed after the material reaches its melting temperature. This occurs due to an increase in material absorption after phase transformation. Once melting begins, the material absorbs more energy, which accelerates penetration. This behavior highlights the importance of considering temperature-dependent properties in thermal analysis.

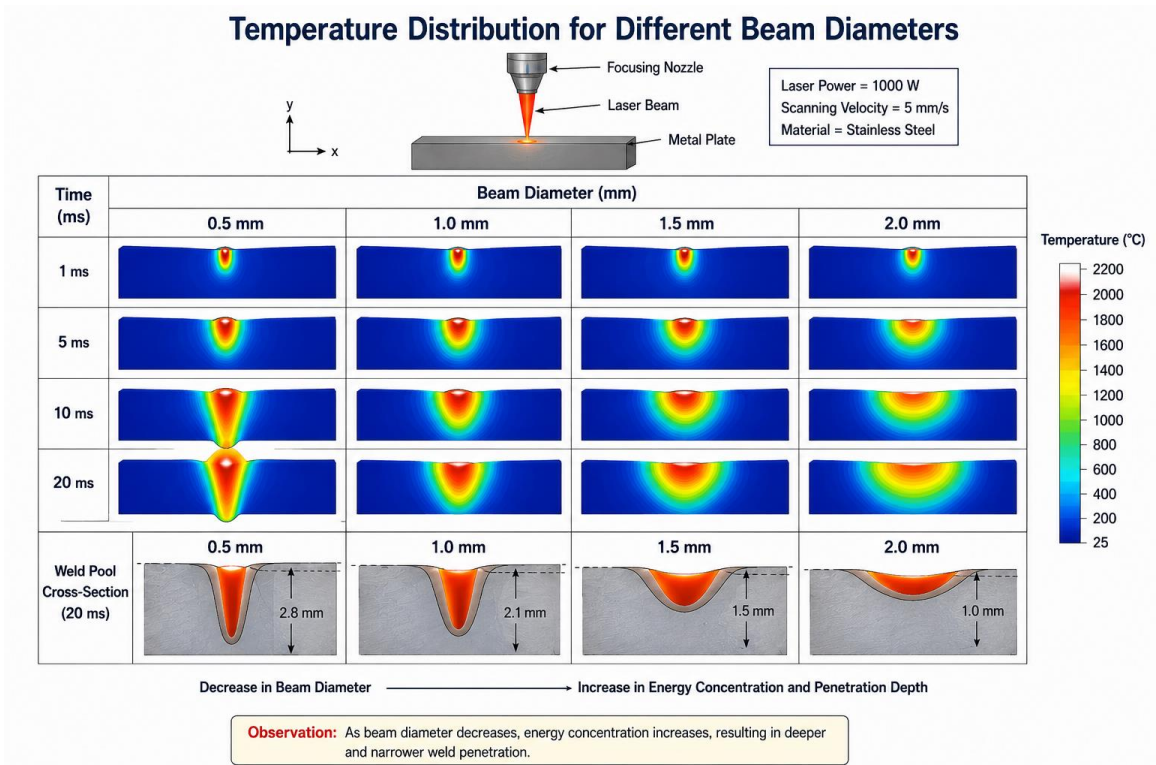
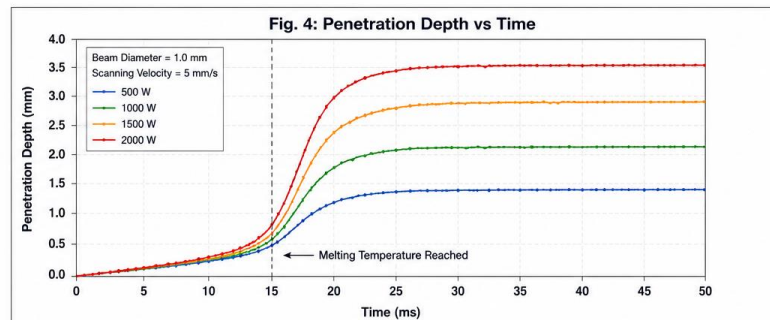
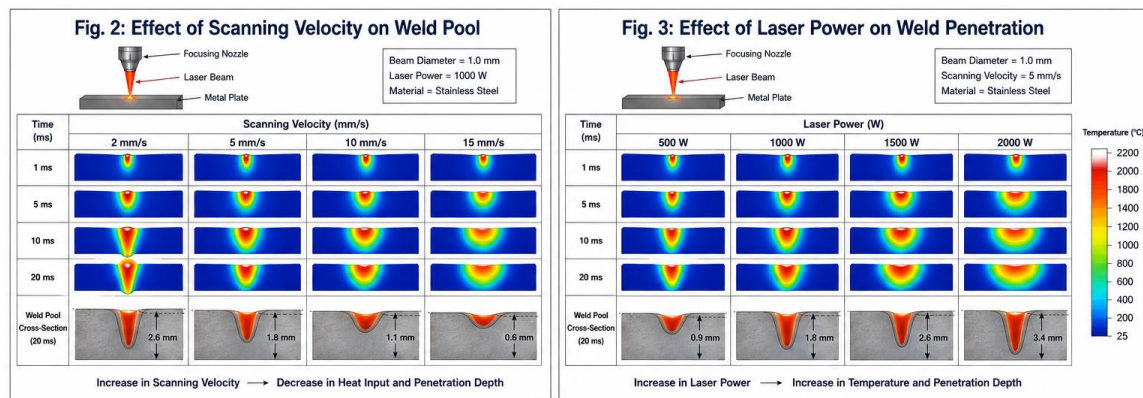


Fig-1



**Observation:** A sudden increase in penetration depth is observed after the material reaches melting temperature. This is due to increased absorption of laser energy after phase change, which accelerates the penetration process.

**VI. References**

1. Morton & Mayers, 2005
2. Lienhard, 2005
3. Steen, 1998