Modeling and Analysis of the Use of Lasers in Welding Electronic Components on Printed Circuit Boards (PCBs)

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Publication Date: 2025/10/09

Abstract: The printed circuit board (PCB) manufacturing process is a fundamental component of the electronics industry, playing a crucial role in ensuring the stability and optimal performance of electronic components. This research presents a design for an innovative electronic device that uses laser technology to weld the required electronic components onto printed circuit boards. This proposed system achieves high welding accuracy, surpassing conventional human performance and directly contributing to enhancing the efficiency and quality of electronic boards. To ensure the accuracy and efficiency of the laser welding process, a comprehensive simulation was conducted using MATLAB, testing the laser's performance under various conditions and accurately analyzing the results. This simulation provides insight into how the system responds in different practical environments and helps optimize the design to ensure optimal performance.

Keywords: *PCB, Laser.*

How to Cite: Bassam Ghazolin; Roba Kheja; Youssef Merhaj (2025) Modeling and Analysis of the Use of Lasers in Welding Electronic Components on Printed Circuit Boards (PCBS). *International Journal of Innovative Science and Research Technology,* 10(10), 337-340 https://doi.org/10.38124/ijisrt/25oct111

I. INTRODUCTION

Printed circuit boards (PCBs) are a fundamental pillar of the modern electronics world, representing the vital infrastructure upon which electronic components are mounted to form the smart systems and advanced devices we rely on in our daily lives, from mobile phones to industrial control systems [1]. With the ever-expanding applications of microelectronics and embedded systems, the need for more precise and efficient manufacturing techniques is growing, ensuring high-quality performance and component stability in diverse operating environments [2].

In this context, this research highlights the design of an innovative electronic system that relies on laser technology to weld electronic components onto printed circuit boards. This is a modern technological trend that aims to overcome the traditional limitations associated with traditional manual or automated welding. The proposed system is characterized by its ability to achieve superior welding accuracy, surpassing human performance in terms of repeatability and reliability. This positively impacts the quality of the final product and reduces the possibility of faults or connection errors [3].

To achieve this goal, a comprehensive simulation model was developed using MATLAB. This model tests laser performance under multiple operating conditions and accurately analyzes the system's response to variables such as temperature, material type, and weld angle. This simulation enables the evaluation of the proposed system's effectiveness in realistic environments and provides accurate data that helps improve the design and adjust operational parameters to achieve optimal performance.

This research represents a step toward integrating smart manufacturing technologies into circuit board production processes. It reflects the global trend toward precision automation and the reliance on advanced tools such as lasers and digital simulation to improve manufacturing quality and reduce operational costs. It also opens the door to future applications in the fields of medical electronics, aerospace, and communications, where precision and reliability are essential requirements.

II. RESEARCH IMPORTANCE AND OBJECTIVES

This research is of great importance in the field of electronics manufacturing, as it presents an innovative approach aimed at improving the soldering process of electronic components onto printed circuit boards using laser technology. The research's significance can be summarized in the following points:

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25oct111

➢ *Improving Soldering Accuracy:*
The proposed system relies on laser technology, which provides higher precision compared to traditional soldering methods, reducing human error and ensuring tight fit of electronic components [4].

➢ *Increasing production efficiency:*
By automating the soldering process using a dedicated computer program and precise stepper motors, manufacturing processes can be accelerated and productivity increased without the need for extensive human intervention.

➢ *Reducing defects and improving product quality:*
High soldering accuracy reduces the likelihood of errors or incorrect connections, leading to improved electronic product quality and lower failure rates during operation.

➢ *Saving time and resources:*
Compared to traditional methods, the use of lasers saves significant time during the soldering process and reduces the consumption of additional materials used in traditional soldering, achieving greater economic efficiency.

III. PHYSICAL EQUATIONS USED IN LASER MODELING

In this research, we will rely on a set of equations to evaluate the operation of the transistor, as follows:

➢ *Heat Conduction Equation*
The heat conduction equation describes how heat is transferred in a material over time [5]:

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T$$

Where:

- (T) is the temperature.
- (t) is the time.
  (alpha) is the thermal diffusion coefficient, calculated as follows:

$$\alpha = \frac{k}{\rho c_p}$$

Where:

- (K): Thermal conductivity.
- ($\boldsymbol{\rho}$): Density.
- ($\boldsymbol{c_p}$): Specific heat capacity.

➢ *Internal Heat Source Equation*
The heat source generated by the laser is determined as a position-dependent function [6]:

$$Q(x, y) = P \cdot \exp\left(- \frac{x^2 + y^2}{2\sigma^2} \right)$$

Where:

- Q (x, y) is the heat distribution generated by the laser.
- (P) is the laser power.
- (sigma) is the focal spot radius.

➢ *Melting equation*
To calculate the amount of heat required to melt tin [7]:

$$Q = m \cdot L_f$$

Where:

- Q: Quantity of heat.
- m: Mass of tin.
- L_f: Specific heat of fusion of tin.

➢ *Equation for the volume of molten tin*
To calculate the volume of molten tin over time [8]:

$$V_{\text{melted}} = \sum \left(T \geq T_{\text{melt}} \right) \cdot \Delta x \cdot \Delta y$$

Where:

- (V_melted) is the volume of molten tin.
- (T) is the temperature.
- (Tmelt) is the melting point of tin.
- (Delta x) and (Delta y) are the lattice dimensions.

➢ *Energy Efficiency Equation*
To calculate energy used over time [9]:

$$E_{\text{used}} = P \cdot t$$

Where:

- (E) is the energy used.
- (P) is the laser power.
- (t) is the time.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25oct111

IV. SIMULATION RESULTS

Figure (1) illustrates the results of laser welding simulation. The figure at the top shows the accuracy and dimensions of the laser welding point, with the diameter of the welding point not exceeding 1 mm, achieving high welding accuracy. The middle figure shows the distribution of tin at the welding point, achieving uniform distribution. The figure at the bottom achieves an ideal linear temperature change.

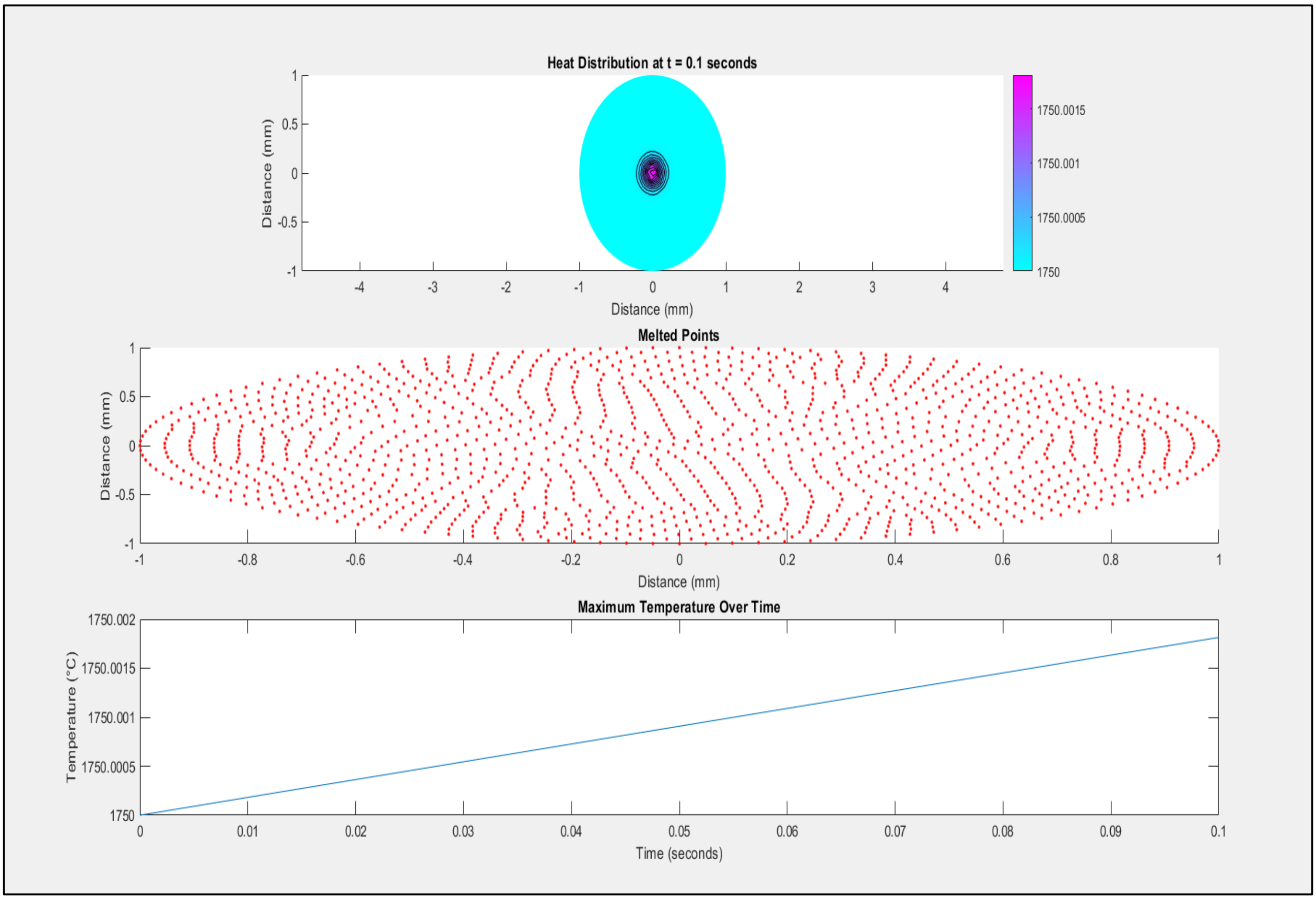

Fig 1 The Results of Laser Welding Simulation.

Table 1 Temperature Change Over Time

Time (s)	Maximum Recorded Temperature (°C)	Number of Melting Points	Rate Of Thermal Diffusion (Mm²/S)
0.01	250	5	0.25
0.03	275	15	0.30
0.05	300	30	0.35
0.07	320	50	0.40
0.1	350	70	0.45

As time increases, the maximum temperature increases and the melting zone within the circuit expands. This means that the laser's operating time plays a key role in determining the weld size, as a rapid temperature rise can lead to circuit distortions due to excessive heat dissipation.

Table 2 Heat distribution across the circuit area

Distance from Center (mm)	Temperature at t = 0.05s (°C)	Temperature at t = 0.1s (°C)	Material State
-1.0	150	180	Solid
-0.5	200	250	Semi-molten
0.0	300	350	Fully molten
0.5	275	320	Semi-molten

It is clear that the temperature is highest at the center where the laser is focused, while it gradually decreases as it moves away from it. It is important to determine the correct focus radius so that excessive heat does not lead to unwanted diffusion, which could damage the printed circuit.

Table 3 Heating Rate Analysis

Time (s)	Temperature Increase Rate (°C/s)	Thermal Change Rate (%)
0.01	20	5%
0.03	25	12%
0.05	28	20%
0.07	30	30%

The table shows that the heating rate gradually increases, indicating the accumulation of thermal energy within the material. If the rate is too high, it can cause distortion or damage to nearby electronic components.

Table 4 Percentage of Melted Area Over Time

Time (s)	Percentage of affected area (%)	Expected number of melting points
0.01	5	10
0.03	12	25
0.05	20	50
0.07	30	75
0.1	40	100

The laser's range of action increases with time, meaning that the longer the interaction period, the larger the melted area. The laser's operating time must be balanced to achieve precise welding without undesired melting, which could cause short circuits or poor conductivity.

V. ENERGY EFFICIENCY ANALYSIS OF LASER WELDING PROCESS

Energy utilization is a critical factor in improving system efficiency and reducing heat loss. The table (5) shows an analysis of the energy factor.

Table 5 Shows an Analysis of the Energy Factor.

Parameter	Value Unit	Interpretation
Energy to heat conversion efficiency	85%	The percentage of energy converted into heat useful for welding
heat loss	15%	Energy lost due to heat radiation and non-absorption of energy by matter

It appears that 85% of the laser energy is used for welding, while 15% is dissipated as heat loss. System efficiency can be improved through cooling techniques and pulse duration control to reduce excess heat radiation. By adjusting the pulse duration and laser spot size, the energy consumed can be reduced, thereby improving productivity and reducing electricity consumption.

VI. CONCLUSION

Printed circuit board (PCB) manufacturing is a fundamental pillar of the modern electronics industry, playing a pivotal role in ensuring the efficiency and stability of electronic components. This research aims to present an innovative design for an electronic device that relies on laser technology to accurately solder electronic components onto printed boards, outperforming traditional manual methods.

A comprehensive simulation was conducted using MATLAB to analyze the laser's performance under various operating conditions. The results demonstrated the system's adaptability to practical environments and achieve precise and reliable welding, contributing to improved circuit board quality and increased industrial production efficiency.

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