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A Numerical Approach for Predicting Temperature Distribution, Heat Flow, and Material Deformation of Printed Circuit Board during Laser Soldering

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ABSTRACT

This paper presents a numerical simulation approach using the finite element method (FEM) in ANSYS software to overcome the limited accessibility of laser soldering machines which are very expensive. The study aims to examine the viability of simulating a laser soldering process using ANSYS steady-state thermal simulation and produce accurate predictions for temperature distribution, heat flow, and deformation of the material during the process. A Gaussian laser beam equation is used to analyse the interaction between the laser beam and metallic components, particularly on PCB boards. This paper evaluates the properties of a laser beam and the Sn-3.0Ag-0.5Cu (SAC305) lead-free solders which are commonly used in electronic industries. As a result of the thermal analysis, the temperature distribution within the solder spots, as well as the copper as printed circuit board (PCB) can be determined, whereas the mechanical analysis of the materials can be determined by looking at their deformation and stress in the system. The results show that the laser beam effectively contains heat within the solder contacts, reducing the risk of excessive heat transfer. The copper acts as an efficient heat sink, managing thermal energy during the process. However, the solder point experiences substantial deformation and stress, indicating potential limitations in its performance. Nonetheless, the neighbouring components and solder joints exhibit a factor of safety, ensuring the overall safety and reliability of the system.

1. Introduction

Throughout the electronics industry, laser soldering has become increasingly popular due to its precise and efficient performance. It is widely used in the connection of electronic components and printed circuit boards (PCB) due to its special advantages of local heating, non-contact heating, rapid heating and rapid cooling, and short bonding time, which can reduce thermal damage during soldering [1, 2]. The process of laser soldering involves using a laser beam to melt and join metal components. Laser soldering is effective for rear attachment of components, small lead pitch reflow, simultaneous connections of multiple points, and soldering in restricted spaces [3]. The

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miniaturization and improved integration of microelectronic devices increased the possibility of flexible and wearable substrates, in which the temperature and time of bonding processes are crucial factors for reliability. In general, substrates had a relatively low heat resistance and were easily affected and deformed by a process temperature in the joining process. A lower joining temperature and a heat-affected process were recommended for these applications. Therefore, laser soldering provides a more promising process than conventional reflow soldering owing to its various advantages and applicability to miniaturized electronic integration [4-6]. The solder joints processed by laser have superior impact reliability than those prepared by conventional reflow soldering. Moreover, the growing popularity of lasers in flexible electronics has attracted great attention from researchers, and the study of laser heat sources on any materials system can aid in understanding the mechanism of laser-materials interaction [4].

The microstructure evolution at the interface of the solder is dependent on the laser-material interaction [4]. During laser soldering, a variety of intermetallic compounds (IMCs) are created at the joints, with the composition varying depending on the energy used. The interfacial IMC thickness rises when joints age and lose some of their shear strength [7]. According to Liu *et al.,* [8], the interfacial compound evolution during consecutive reflows was shown to be impacted by the initial laser soldering, according to transmission electron microscopy. Meanwhile, Zhang *et al.,* [9] mentioned that a quick laser beam during reflowing treatment greatly boosts the strength of the solder connections due to grain refinement and Cu alloying effects. In addition, the laser processing parameters namely power (P), scan speed (Vscan), etc. and materials composition mainly define the resulting interfacial microstructure of the SAC/Cu system. The transient and spatially non-uniform temperature profiles during laser soldering led to interfacial microstructural evolution different from that of conventional isothermal reflow soldering [4].

Furthermore, Lee *et al.,* [10] simulation results show that laser reflow and laser processes significantly reduce warpage compared to mass reflow, thanks to selective heating, directional laser beam properties, and lower substrate temperature, mitigating thermal expansion mismatch. In another study, Kim and Choi [11] experimental measurements and simulations result to confirm the effectiveness of laser reflowing, with the maximum shear strength increasing when beam shaping is applied. Controlling the laser power density on the PCB remains a challenge for implementing this process effectively. Tan *et al.,* [12] discussed that the exposure period and power setting have an impact on the soldering temperature. Temperatures rise with increasing power levels and establishing well-wetted solder junctions in flux-less applications requires reaching a soldering temperature greater than the melting temperature. Thus, laser soldering at specified parameters yields more promising outcomes [7]. Nicolics and Hoble [13] highlight the delay in wetting onset compared to the melting point of the solder and the significance of the wetting temperature above the melting point under high heating rates. The laser process parameters, including laser output power and laser output time, are the most fundamental and significant factors. The reason lies in the fact that SnAgCu solder alloys are difficult to melt and spread under the condition of low laser output power or short soldering time, while the excessive laser output power or long soldering time may lead to the thermal breakdown of PCB substrate [1]. Safdar *et al.,* [14] discussed the importance of laser beam geometry in manipulating temperature distribution during the laser melting process. Different beam geometries have distinct features that can be selected based on process requirements. Beckett *et al., [*15] models reveal the significance of factors such as copper thickness and internal connectivity, and provide insights into heat flow mechanisms and parameter influences, reducing the need for trial, and error experimentation in determining suitable laser soldering process parameters. Gawyer *et al.,* [16] simulations confirm that the laser sweeping method is considered an attractive alternative to hand soldering due to improved solder joint quality and reduced component wastage. Meanwhile, Zheng *et al.,* [17] focused on laser soldering of Micro-USB connectors and conducted a sequential thermal-mechanical analysis to evaluate thermal characteristics and residual stress distribution. The analysis revealed that increasing laser power led to higher thermal distortion and stress in the solder joints.

A numerical approach is increasingly applied in the research of laser soldering of electronic components, and many calculation models based on various assumptions have been proposed [1, 18]. The load-displacement curves analysis using finite elements by Khan and Yosoff [19] stated that energy absorption per unit mass reflects the specific energy absorption, the maximum value of specific energy absorption indicates the optimal size and the area under the load-displacement curve represents the total absorbed energy. Finite element modelling was utilized by Azizan *et al.,* [20] to forecast the mechanical reactions and failure of laminates made of fibre-reinforced polymer (FRP). Kunwar *et al.,* [6] model the heat and mass transport mechanisms that occur during laser soldering and the Jackson parameter is used to explain the reason distinct IMC morphologies have appeared. Yang *et al.,* [1] conducted experiments on laser soldering and they stated that it can be difficult to precisely measure these characteristics of temperature and thermal stress of solder connections when laser soldering. The researchers suggest a unique finite element-based 3D transient numerical model solve this. The outcomes of the numerical simulation show that the relationship between laser output power and output time and solder joint temperature, thermal stress, and deformation is direct. Thus, it is needed to set up a novel numerical model to simulate the influence of the laser soldering parameters on the microstructure and performance of the solder alloys, which is used to have good consistency with the experimental results [1].

Therefore, this study aims to investigate the feasibility and accuracy of using ANSYS steady-state thermal during the laser soldering process by using the developed numerical model. By modelling the laser beam's interaction with the metallic components and forecasting the temperature distribution, heat flow, and material deformation throughout the operation, this simulation technique is anticipated to properly represent the real soldering process.

2. Methodology

The ANSYS steady-state thermal simulation approach was used in this work to model and simulate the temperature distribution, heat transport, and material deformation during the laser soldering process on PCB boards. A robust finite element analysis programming with a focus on steady-state simulations and thermal analysis is called ANSYS steady-state thermal. To simulate the laser beam's interaction with the PCB board, we utilized the Gaussian laser beam equation. This equation explains how a laser beam's strength varies as it moves through a material. The spatial distribution of laser intensity is frequently represented by the Gaussian beam profile. It is significant to remember that several assumptions were made throughout the modeling process, which affects how accurate the simulation findings are. These presumptions covered things like the characteristics of the laser beam, the boundary conditions, and the geometry.

Gaussian laser beam equation [21]:

$$I(r) = I_0 \exp\left(\frac{-2r^2}{w(z)^2}\right) = \frac{2P}{\pi w(z)^2} \exp\left(\frac{-2r^2}{w(z)^2}\right) \tag{1}$$

where I_0 is the peak irradiance at the centre of the beam; *r* is the radial distance away from the axis, and *w(z)* is the radius of the laser beam.

By using Eq. (1), we can calculate peak power and irradiance.

Peak Power: $I_0 = \frac{2P}{\pi w(z)^2} = \frac{2*100}{\pi*1.25^2} = 40.743\ w/mm^2$

Irradiance *I(r)*: $40.743 \exp\left(\frac{-2r^2}{w(z)^2}\right)$

It can be shown from Table 2 and Figure 1 that the laser beam's peak intensity is approximately 40.8 W/mm2. This number denotes the highest irradiance attained at the beam's centre. The peak intensity of 40.8 W/mm2 will be used in the numerical analysis and any additional calculations concerning the irradiance of the laser beam based on this information.

Table 1
Starfiber 300 P beam properties

Profile	Value
Power (W)	100
Pulse length (ms)	50
Beam radius (mm)	1.25

Table 2
Irradiance for 10 step numbers and step size 0.125mm

Radius (mm)	Intensity
0.00	40.743
0.125	39.936
0.250	37.610
0.375	34.031
0.500	29.585
0.625	24.711
0.750	19.831
0.875	15.291
1.000	11.328
1.125	8.062
1.250	5.513

Due to its unique properties, the Sn-3.0Ag-0.5Cu alloy, comprised of 3.0% silver, 0.5% copper, and the remaining tin, is a favoured option for laser beam soldering. This alloy allows for accurate and localized heating during the soldering process without causing undue heat damage to neighbouring components because of its low melting temperature and eutectic nature. Its eutectic makeup guarantees the development of a consistent and dependable solder connection. The alloy also possesses advantageous mechanical characteristics, such as adequate tensile and yield strengths, which guarantee the structural integrity and endurance of soldered connections (Table 3). Sn-3.0Ag-0.5Cu is an appropriate material for laser beam soldering applications due to these characteristics.

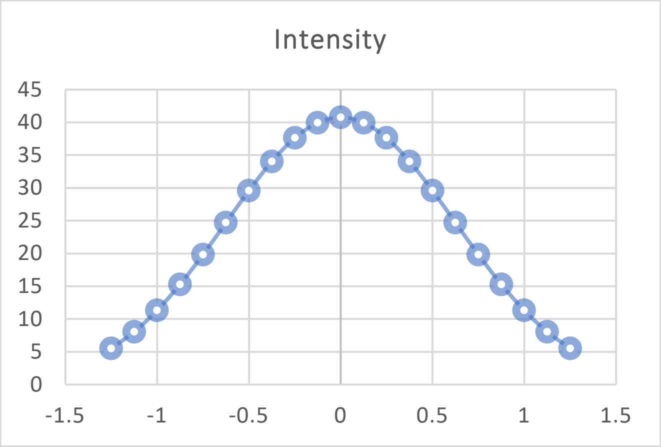

Fig. 1. Laser beam Irradiance intensity profile

Table 3
Material properties of Sn-3.0Ag-0.5Cu

Profile	Value
Tensile strength (MPa)	41.1
Yield strength (MPa)	34.2
Young’s Modulus (GPa)	50
Poison ratio	0.36
Specific heat (J/g K)	0.23
Thermal Conductivity (%) 25C	63.2
Thermal Conductivity (%) 60C	-
Thermal Conductivity (%) 100C	0.173

The PCB measures 70mm in length, 52mm in width, and 1mm in thickness as illustrated in Figure 2. The diameter of the solder points on the PCB, which correspond to the size of the soldering regions where components are joined, is 6mm. The thickness or elevation of the soldered areas above the surface of the PCB is indicated by the solder points' height, which is stated as 0.8mm. The layout and arrangement of the electrical components on the board are greatly influenced by these dimensions, which define the physical design of the PCB.

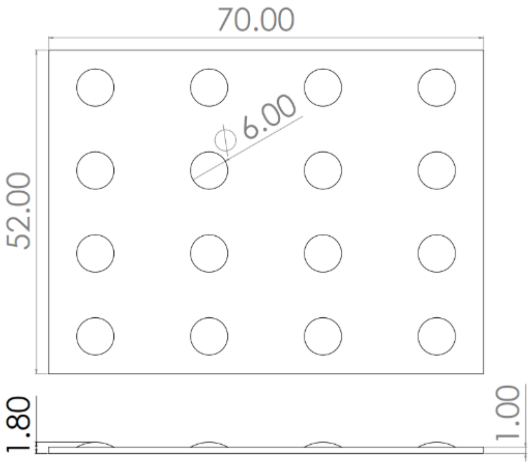

Fig. 2. Dimensions of PCB Geometry

3. Results

3.1 Thermal Study

The thermal analysis of the laser beam simulation yielded significant information on the temperature distribution and heat flux within the solder spots and the copper board. The highest thermal stress the solder joints had to withstand as can be seen in Figure 3, where the maximum temperature calculated at the solder spots was 335.36°C. On the other hand, 56.81°C was the lowest temperature ever recorded within a solder point. These temperature data provide details on the solder connections' thermal behaviour and their ability to withstand the heat generated during the laser soldering process. According to Yang *et al.,* [1], the initial temperature for Sn-Ag-Cu solder and PCB substrate was assumed to be ambient temperature (T0 =293.15 K). After Sn-Ag-Cu solder absorbed laser energy, some portions of the energy would spread into the surrounding environment by the thermal convection and thermal radiation from the surfaces of the solder and PCB substrate, and the rest part of the energy was used for heat conduction and heat accumulation inside the solder and the PCB substrate.

In Figure 4, a cross-section view of the solder points, it was noticed that the temperature distribution profile did not extend over the Sn-3.0Ag-0.5Cu solder sites through the copper board. This result indicates that the heat from the laser beam was effectively contained inside the solder contacts, lowering the potential of excessive heat transfer to the neighbouring components. According to the investigation, the copper board had a higher heat flux of 47.57 W/mm2 (Figure 5). The heat flux, which provides crucial information on the system's thermal energy loss, is a measure of the rate of heat transfer per unit area. Due to its improved heat flux, the copper board proved to be an effective heat sink, collecting, and distributing the thermal energy generated during the laser soldering process.

The temperature gradient of the PCB board, with the peak temperature observed at the solder point made of Sn-3.0Ag-0.5Cu, while the copper (Cu) board exhibits relatively lower and more stable temperatures has been shown in Figure 6. The temperature gradient plot showcases the variation in temperature along the surface of the PCB board. At the solder point, where the laser beam is focused, the temperature reaches its peak value. This high temperature is primarily attributed to the energy absorption and heat generation in the solder material. In contrast, the copper board, which acts as a heat sink, maintains a relatively lower and more uniform temperature compared to the solder point. The temperature of the copper board fluctuates around the range of 70 to 80 degrees Celsius, indicating its ability to dissipate heat effectively and regulate thermal distribution.

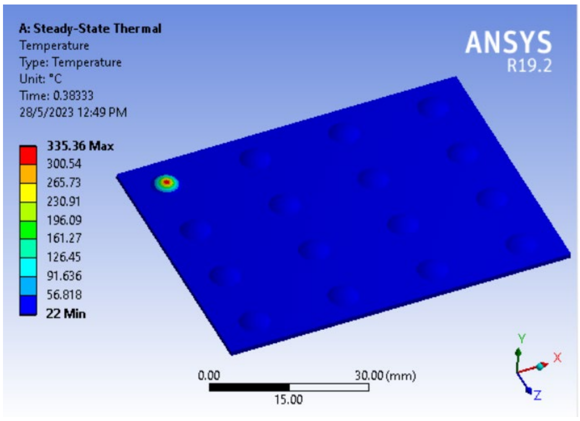

Fig. 3. Temperature distribution of solder point

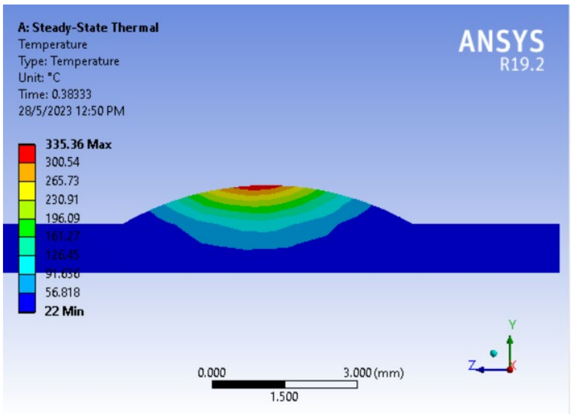

Fig. 4. Cross-sectional display of temperature distribution

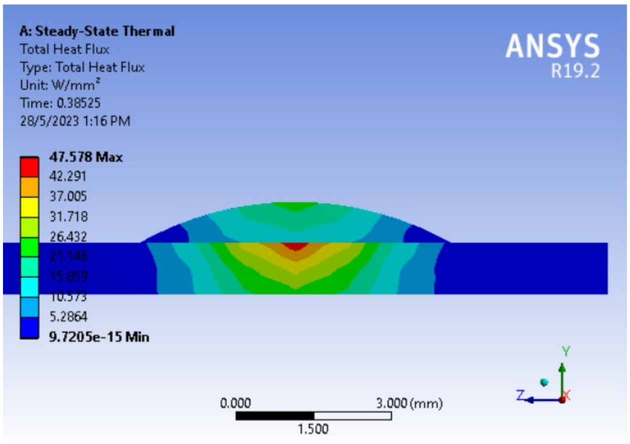

Fig. 5. Heat flux characteristic of solder point and copper PCB

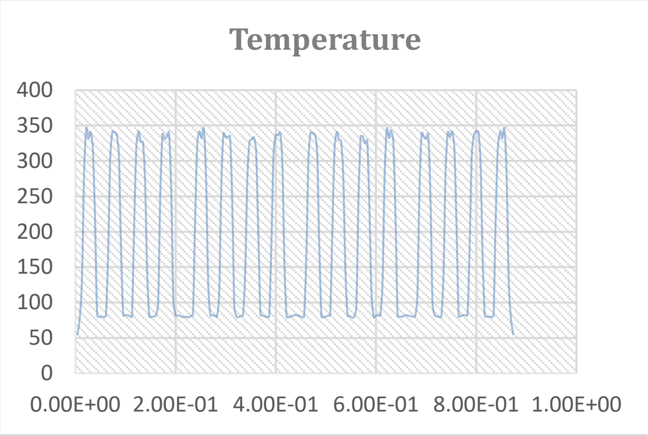

Fig. 6. Peak temperature of each solder point

Figure 7 represents combines the laser beam irradiance profile and the temperature distribution on the solder point, providing valuable insights into their relationship. The beam area of 2mm and the irradiance profile covering the range from -1 to 1 are depicted. At the centre of the irradiance profile, located at 0, the temperature is recorded at 335.56°C. This coincides with the peak intensity of 40 w/mm2, indicating a strong correlation between the intensity of the laser beam and the resulting temperature rise. At close to the boundaries of the irradiance profile, represented by -1 and 1, the temperature decreases to 230.91°C. Simultaneously, the peak intensity drops to approximately 10 w/mm2. This observation suggests that the closer the boundary area of the intensity profile, the temperature gradually decreases as the irradiance approaches zero. The result from Yang *et al.,* [1], at 14w the maximum temperature recorded, is 222 °C which is much closer to the current result at similar power.

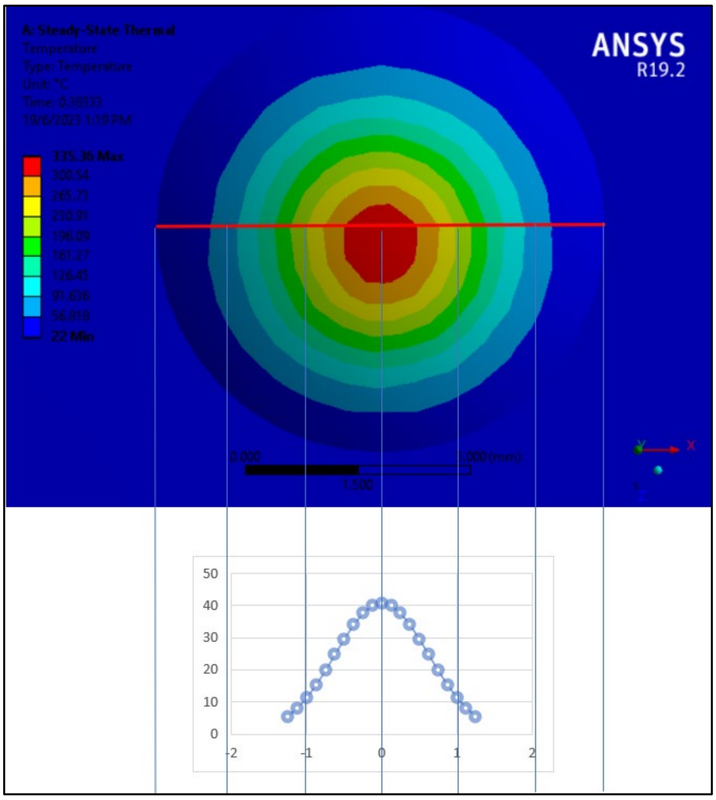

Fig. 7. Laser beam Irradiance intensity and temperature

Furthermore, Yang *et al.,* [1] observed that the laser heating rate and cooling rate had an impact on the temperature distribution and cooling rate of the SnAgCu solder connections. The extended period above the melting point and higher peak temperatures caused by the increased laser output power and output time encouraged solder melting and wetting. A consistent and fine microstructure was also significantly influenced by the cooling rate, with excessive cooling resulting in coarse development. The findings on thermal stress and deformation are consistent with previous research, which shows how temperature gradients affect the durability of materials where the temperature distribution inside the solder joints and the heat flux of the copper board, which demonstrated successful heat containment within the solder contacts and the copper board's effectiveness as a heat sink. The mechanical thermal study showed that the system's structural integrity could withstand some distortion, but the solder point showed a reduced factor of safety, indicating the possibility of deformation or melting. However, the solder joints and adjacent parts displayed greater safety factors, assuring both the protection of those parts and the overall safety of the system.

3.2 Thermal Study

The system's mechanical thermal examination produced significant results regarding its safety. The maximum deformation measured was 0.015mm as represented in Figure 8, showing that the materials underwent displacement or deformation because of heat stress. The thermal effect was only considered, while the external load force and volume force were ignored. Since the PCB substrate was fixed on the working platform, then the fixed deformation conditions could be added on the left, right and bottom surfaces of the PCB substrate as the boundary conditions for thermal stress and deformation field while thermal deformation for other PCB surfaces is fully released [1]. In order to make sure the system's structural integrity is preserved, this value must be compared to permitted deformation limits. The highest stress could be estimated at 116.92 MPa as shown in Figure 9 which shows the internal forces that were placed on the materials. To make sure that the system can tolerate thermal loading without running the danger of material failure or structural damage, it is critical to compare this stress value with the material's yield strength or permitted stress limits. The solder point has a factor of safety of 0.29 (Figure 10). This low number implies that the applied stress approaches or surpasses the material's yield strength, which means that the solder point is likely to experience substantial deformation or even melt. But it is crucial to remember that the solder joint's primary function, which is to make attaching components easier, still applies in this case. On a positive note, the surrounding area of the solder point exhibits a factor of safety (FOS) of at least 5. This indicates that the neighbouring components and solder joints in the vicinity remain within a safe range of stress, reducing the risk of failure. This reassures the overall safety of the system, as the critical components are adequately protected.

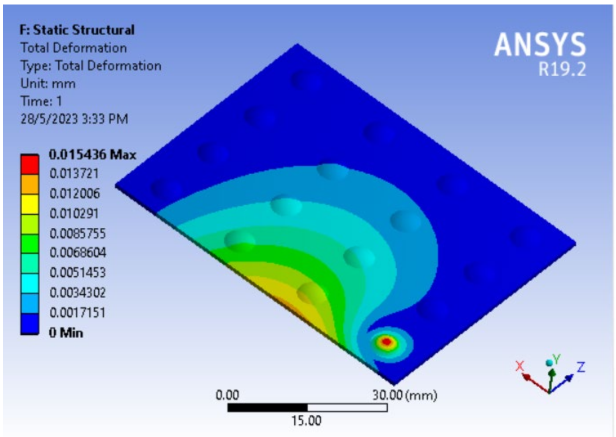

Fig. 8. Deformation result of static thermal analysis

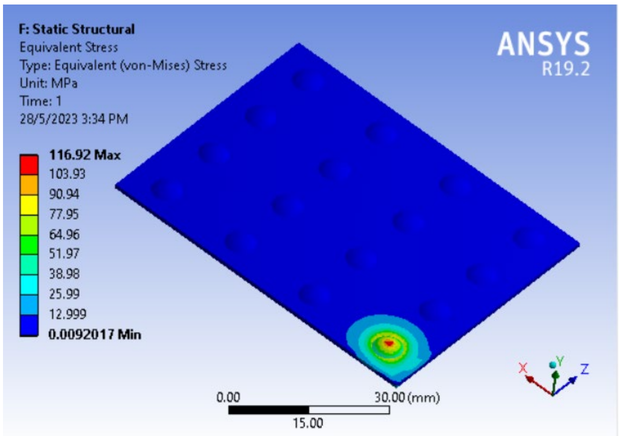

Fig. 9. Stress result of static thermal analysis

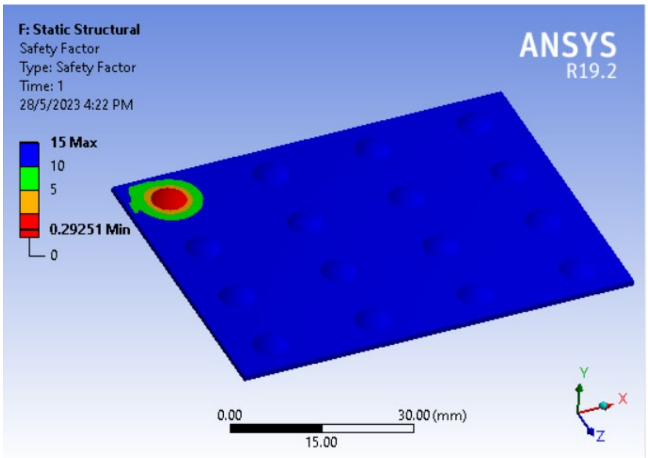

Fig. 10. Factor of safety result of static thermal analysis

4. Conclusions

In conclusion, this work indicates the possibility of simulating a laser soldering process utilizing numerical simulation methods, notably ANSYS steady-state thermal simulation. This simulation technique offers a cost-effective substitute for pricey physical equipment by precisely projecting the temperature distribution, heat flow, and material deformation throughout the operation. With a special emphasis on PCB boards and the Sn-3.0Ag-0.5Cu alloy frequently used in the soldering process, the analysis concentrated on the interaction between the laser beam and metallic components. The laser beam efficiently restricted heat inside the solder connections, limiting excessive heat transmission to nearby components, according to the thermal study. During the soldering process, the copper board's superior heat sink qualities allowed for efficient thermal energy management and distribution. Significantly, the solder locations showed significant distortion and stress, proving good bonding and solid solder connections. In laser soldering procedures, this distortion is to be expected and appreciated since it indicates a successful joining and increased mechanical strength. According to the simulation findings, the suggested numerical model for ANSYS steady-state thermal simulation can offer insightful explanations of the behaviour of a laser soldering process. Without the need for physical equipment, it provides a useful and affordable technique to anticipate process performance and optimize soldering parameters. Manufacturers may increase the quality and dependability of their soldered connections by considering the thermal distribution, heat flow, and material deformation.

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