A COMPUTATIONAL STUDY OF LASER ETCHING PARAMETERS ON

SILICON PLATE

by

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Dr. Yogesh Jaluria

And approved by

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New Brunswick, New Jersey

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ABSTRACT OF THESIS

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THESIS DIRECTOR:

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In this research work, the effect of laser etching parameters are studied for the computational analysis of silicon plate. The silicon plate model was generated and thermal transient analysis was simulated in ANSYS Workbench. The model was studied as a function of laser etching parameters such as laser intensity, cutting speed, spot size. For the simulation, operating parameters were moving heat flux, thermal convection, radiation and material properties with temperature-dependent thermal conductivity, latent heat of fusion and vaporisation. Material surface and the cross-section was observed for the temperature distribution profile of the material at the same location.

For simulation, 3D Flat plat model of 20 x 20mm with a thickness of 1mm were generated. The model was simulated for, laser intensity of 2000, 3800 and 10000 W/mm^2. Also, for scanning speed of 50, 200, 500 mm/s. And, for the spot size of 0.05, 0.08 and 0.15mm radius. Other parameters were kept constant for each case.

2-D plots were generated to analyse the results of laser etching parameters on the temperature distribution. Images are displayed with temperature distribution across the plate thickness and surface of the plate.

The results demonstrate that laser etching parameters had an influence on the temperature distribution. In this way, laser etching parameters can be investigated for industrial use.

ACKNOWLEDGEMENT

I would like to take this opportunity and sincerely thank my advisor Dr. Yogesh Jaluria for his technical advice, support and pushing me to develop my thesis. Without his guidance, motivation and encouragement, I would not have able to complete my thesis. I always received invaluable guidance as well as concrete and patient advice through my thesis.

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CHAPTER 1

INTRODUCTION

The conventional machining processes have a limitation when using on the large workpiece, advanced engineering materials, complicated design features and on complicated shapes. To overcome this, the different advance machining process has been developed. One of the Advance machining processes which can be used on the wide variety of the material is Laser machining process. Laser machining process has made significant development in recent years as it is low operational cost and high precision. Different laser machining process can be implemented depending upon the application and the material. The right amount of energy at the right place and at right time is required in the laser machining process.

Laser etching is a part of laser marking which also includes laser engraving and laser annealing**.** In the laser etching process marks on parts are made by melting the material surface. When a high amount of energy is focused on the small amount of surface area, heating, melting and evaporation occur. The amount of energy absorbed by the material should just enough to melt the microsurface. Laser etching parameters play an important role in controlling the process.

1.1 Laser Etching Process

Laser etching is the process where laser beam energy is focused directly on the surface to be marked. The energy generated by the beam is absorbed by the material and the surface of the material get altered[1]. The high amount of energy is focused on the small area, as a result, the surface of the material melts and expands. Just enough energy must be absorbed by the material to melt its microsurface. In the laser etching process, localized changes occur on the surface as the material melts and cools down within milliseconds.

Black, white and grey coloured etching can be generated using laser etching. Permanent marking such as data matrix codes, serial numbers, barcodes and logos are created on the material surface by laser etching. Permanent marks are created on the part, which makes it easy to identify the part at the time of the replacement, this is helpful in medical device manufacturing. The automotive industry adopted laser etching to identify parts during the assembly process.

To get the highest production rate with the best finishing quality laser parameter plays an important role. This is why, in this research paper, the effect of laser etching parameters such as laser intensity, spot size and scanning speed on thermal distribution across the silicon plate thickness is studied.

1.2 Literature Review

The study of laser etching process of important industrial materials is crucial. The laser etching parameters have an important role in deciding the quality of the machining. Kerf width, heat-affected zone and surface roughness are affected by the laser parameters, such as laser power and scanning speed. The experiment was conducted on aluminium alloy by varying laser power and the scanning speed. The results were observed for kerf width and the roughness for different scanning speed and power. The results show that kerf width is increased with the increase of beam power but decreased with the increase of scanning speed. Also, with an increase in beam power surface roughness increases and with an increase in scanning speed surface roughness decreases[2].

Laser marking on IC package is used in the industry for many years. But the contrast of marking on the metal IC package is critical. Ye Kaidong, An ChengWu Discussed the way of using micro-capsule tape and laser to do laser marking on the IC package. Nd:Yag Laser setup is used to investigate the effect of laser parameters and the scanning speed. Marking with a different size and scanning speed are discussed to achieve the scanning speed of 200mm/s[3].

Use of laser etching and cutting in the apparel manufacturing process is studied to create user manual which explains different laser parameters. To choose optimal cutting and etching parameters the experiment was conducted. The velvet cloth sample is used for the experiment. The result was observed for different power and scanning speed and contrast of the etch was observed. The result concluded that use of high-power lead to a hole in the cloth while the use of less power leads to no etching. On the other hand, high scanning speed results in no etch while very slow scanning speed results in a cut-through hole[4].

Temperature distribution across the thin film of Aluminium on a polyimide substrate was simulated on ANSYS. The result was studied for etching rate and etch width by varying laser power and scanning velocity without damaging the polyimide substrate. The simulation was carried out by one laser spot to investigate the relationship between laser parameters and processing conditions. Experimental results are compared with simulation results and they are in good agreement. The result shows the etching width increases with an increase in laser power. Also, the experimental results showed that at high power depth of etching was high enough to damage the substrate[5].

Transferring of laser beam energy arrived at the surface of the workpiece is explained by B.S YILBAS. Laser beam energy at the surface is transferred by conduction into the material. Mathematical modelling of the moving heat source is explained in the paper. Paper also explained the region where evaporation occurs. The experiment was carried out to validate the mathematical model. The results were compared for radial variation of a surface temperature and temperature distribution inside the workpiece. The conclusion was made by observing the mathematical and the experimental results that rapid decay in radial temperature distribution occurs just after 1/e points of the laser power intensity. That suggests substance gain high energy through the absorption process compared to losses due to radial effect of heat conduction[6].

The point, Ellipsoidal and Uniform heat source was studied by M. Van Elsen, M. Baelmans, P. Mercelis, J.-P. Kruth. Analytical solution for the heat conduction equation is explained. The study explained higher temperature can be achieved by selecting source geometry with higher energy flux near the centre or by decreasing the spot size. And paper explains that the peak temperature lies inside the spot[7].

CHAPTER 2

MODEL, SETUP AND VALIDATION

2.1 Material Selection

The laser etching process can be used on metals, plastics, wood, glass and many other materials. Silicon is one of the most important material in the electronic industry. Study of the machining process on Silicon is crucial in developing electronic equipment. Silicon material is selected for the study. Thermal properties of the Silicon are temperature dependent[8].

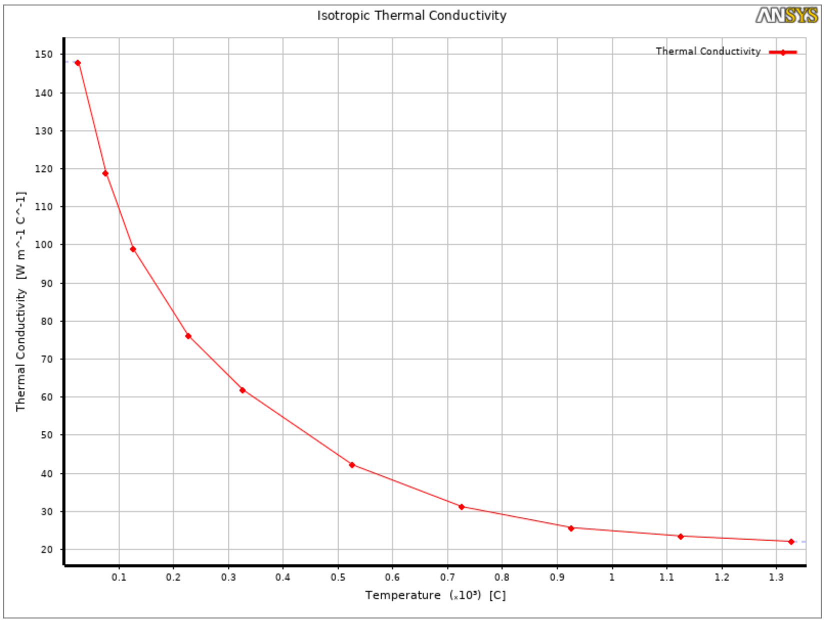


Fig 2.1 Temperature-Dependent Thermal conductivity

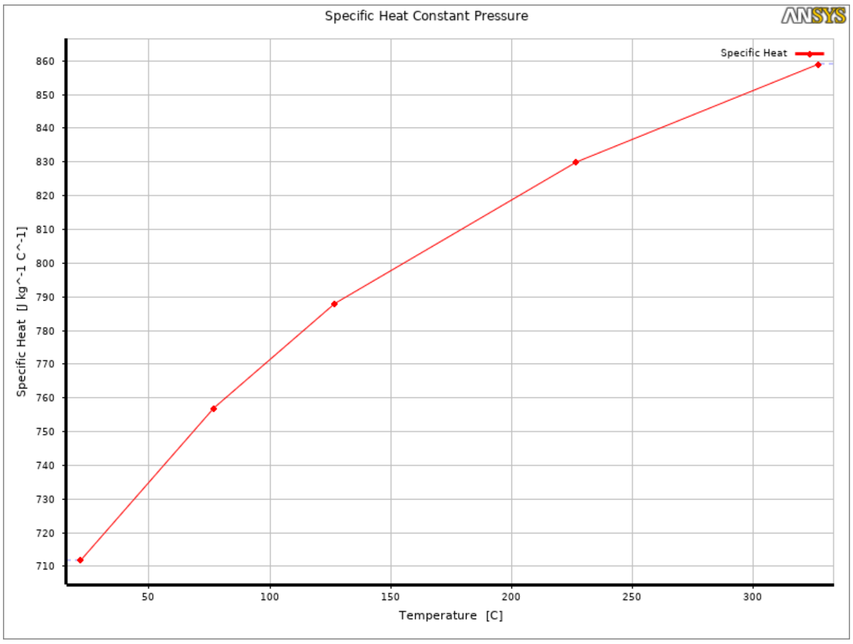


Fig 2.2 Temperature-dependent Specific heat

The table below represents a list of other silicon's properties.

Density (kg/m3)	Melting Temperature (°C)	Thermal Expansion (10^{-6}/ °C)
2330	1414	2.33

Table 2.1 Silicon Thermal Properties

2.2 Computational Model

Silicon plate of dimension 20mm x 20mm and a plate thickness of 1mm is designed for the simulation. The laser is travelling along the centre of the plate. For the results of radial variation of surface temperature symmetric model was considered along the laser path. Finite element method is implemented in ANSYS to solve the heat transfer equations of the moving heat source.

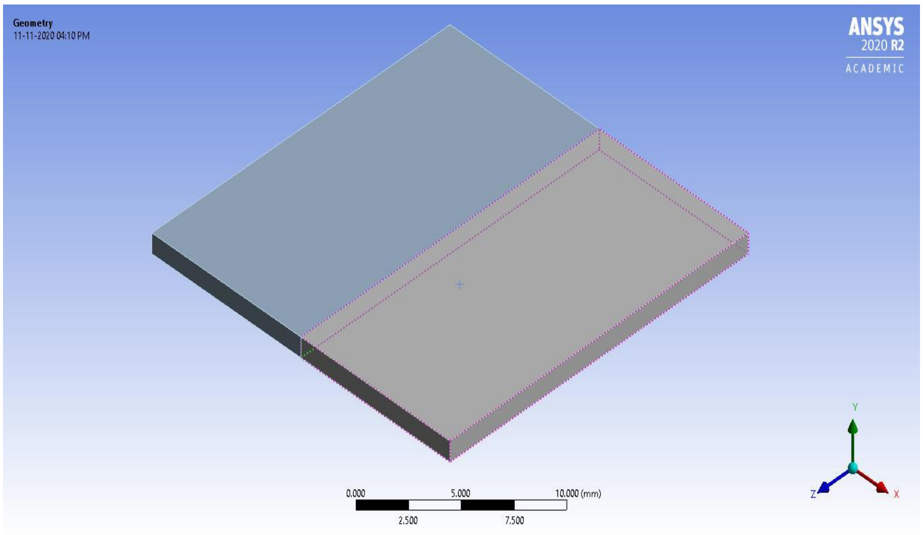


Fig 2.3 Silicon plate model for simulation

To investigate the temperature distribution and the internal relationship between material and laser parameters, all the results are compared at the centre of the laser scanning path.

2.3 Simulation Setup and Validation

The main objective of this simulation is to study the effect of laser parameters on laser etching process. Laser intensity, spot size and scanning speed are selected from the previous studies [5,6]. The number of elements in the meshing of the computational model was fit within the computational compatibility of the educational version of the ANSYS Workbench. For the simulation boundary conditions considered are as:

1. The initial temperature of 22 °C
2. Convective heat transfer coefficient of 20 W/mm^2
3. Emissivity of 0.6

The Simulation is carried out in three parts:

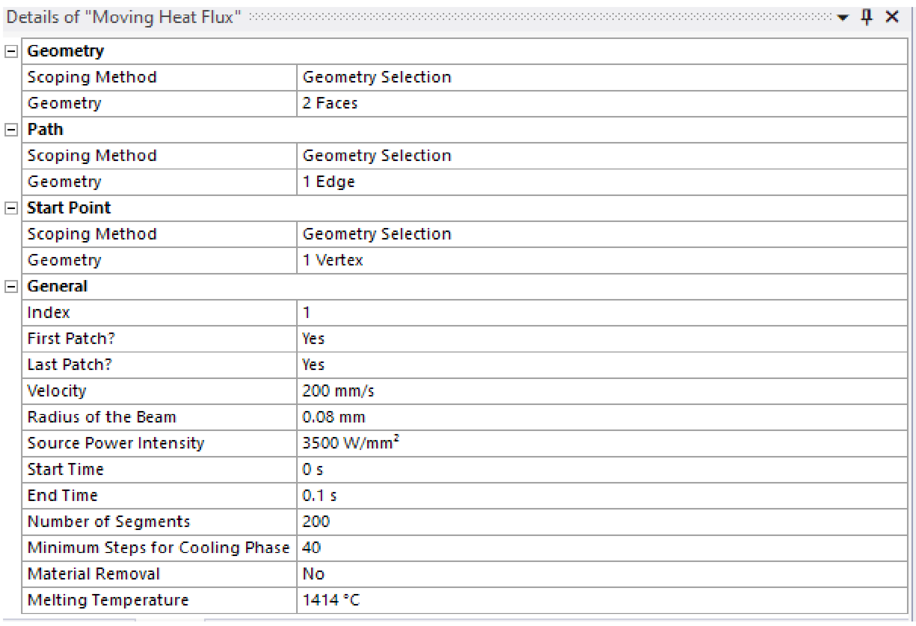
1. Effect of change in laser intensity
2. Effect of change in laser scanning speed
3. Effect of change in laser spot size

Above simulation cases are discussed in the following tables 2.2, 2.3 and 2.4

2.2 Variation in Laser intensity

Case Number	Laser Intensity (W/mm^2)	Scanning Speed (mm/s)	Laser Spot Size (mm)
1	2000	200	0.08
2	3500	200	0.08
3	10000	200	0.08

For the first case, the laser intensity of 2000, 3500, 10000 W/mm^2 is selected while the velocity and spot size are kept constant. The simulation was carried out for 0.1s. Moving heat source extension of ANSYS Workbench is used to solve the simulation. Moving heat flux set up for the case the number 2 is shown in fig 2.4 for the other cases the respective setups are used.



Details of "Moving Heat Flux"

Geometry	
Scoping Method	Geometry Selection
Geometry	2 Faces
Path	
Scoping Method	Geometry Selection
Geometry	1 Edge
Start Point	
Scoping Method	Geometry Selection
Geometry	1 Vertex
General	
Index	1
First Patch?	Yes
Last Patch?	Yes
Velocity	200 mm/s
Radius of the Beam	0.08 mm
Source Power Intensity	3500 W/mm^2
Start Time	0 s
End Time	0.1 s
Number of Segments	200
Minimum Steps for Cooling Phase	40
Material Removal	No
Melting Temperature	1414 °C

Fig 2.4 Moving Heat Flux Set up

2.3 Variation of Laser scanning speed

Case Number	Laser Intensity (W/mm^2)	Scanning Speed (mm/s)	Laser Spot Size (mm)
1	3800	50	0.08
2	3800	200	0.08
3	3800	500	0.08

For the next variation, Laser scanning speed 50, 200, 500 mm/s was studied and laser intensity and spot size were kept constant. The simulation was studied for 0.4, 0.01 and 0.04 sec respectively. Results for the temperature variation and the nature of the moving laser spot is discussed.

2.4 Variation of spot size

Case Number	Laser Intensity (W/mm^2)	Scanning Speed (mm/s)	Laser Spot Size (mm)
1	3800	200	0.05
2	3800	200	0.08
3	3800	200	0.15

For the last part of the simulation, the 0.05, 0.08, 0.15 mm was investigated and laser power and laser scanning speed is kept constant.

The effect of scanning speed and laser power on the depth on the molten pool is studied experimentally on Inconel 718 specimens. Different scanning speed and laser power combination are analysed on three specimens. Figure 2.4 showed that increase of laser power and decrease is scanning speed, the molten pool depth increased. While at 150 W and 1000 mm/s molten pool depth decreased[8].

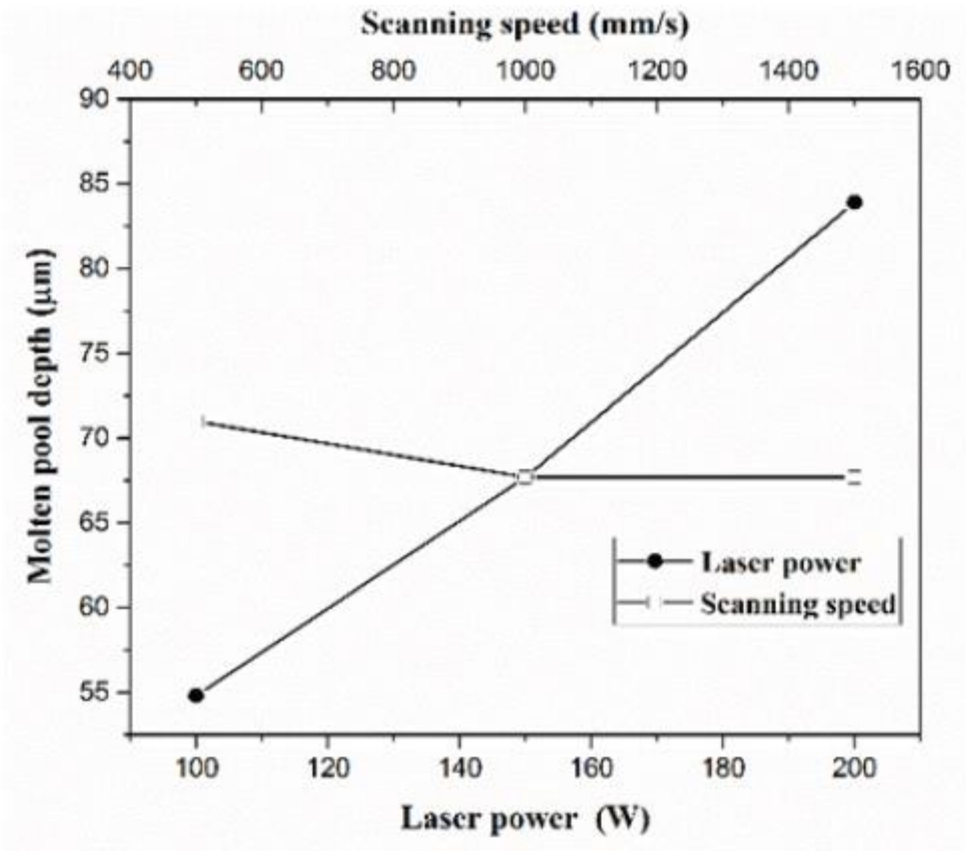


Fig 2.5 The relationship of melt pool depth with laser power and scanning speed[8]

In 1996 B. S. Yilbas studied numerically the effect variation in laser intensity on temperature distribution across the plate thickness and radial temperature variation along the surface. Fig 2.6 shows the surface temperature variation at a different time interval. The result showed surface temperature increased with an increase in laser intensity and the radius of the molten pool.

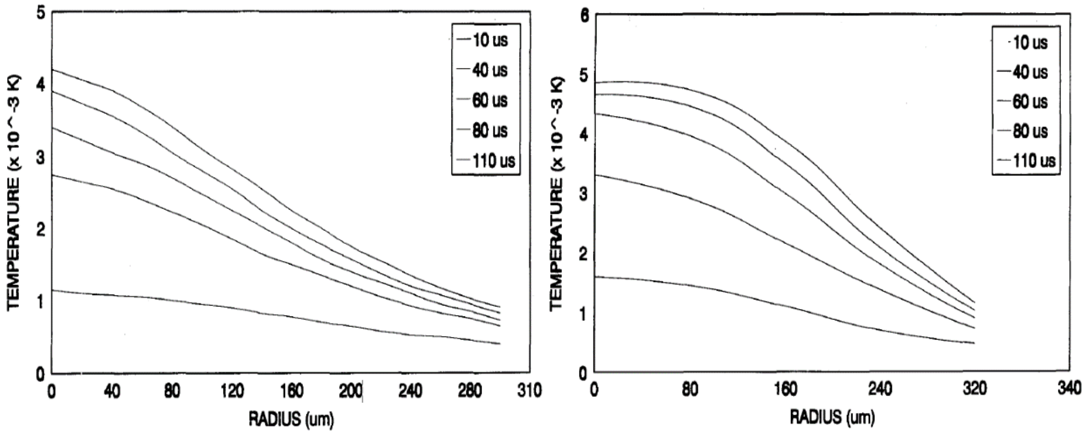


Fig 2.6 Radial variation of temperature at different time intervals for laser intensities of 0.4 x 10^{11} and 0.6 x 10^{11} W/m^2[6]

Also, the effect change intensity on etching width is investigated by Xiaoli Liu and Yuqing Xiong[5]. Fig 2.7 represented simulated and experimental comparison of the effect of laser power on etching width. Paper states that increase in intensity etching width also increased.

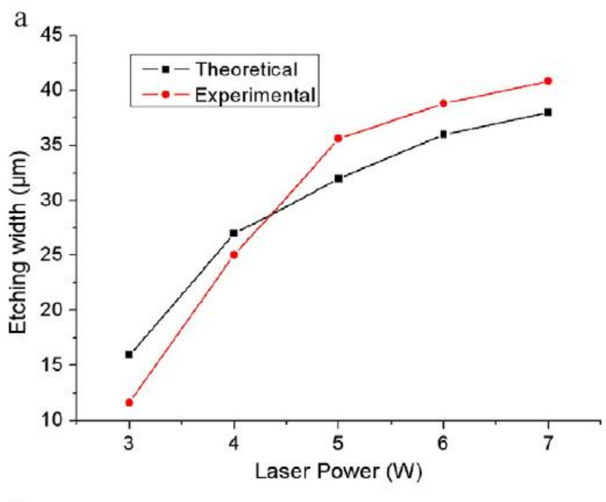


Fig 2.7 Comparison of simulated and experimental etching width[5]

Whitney Rorah explained the use of laser etching in textile manufacturing. Experimental results showed that laser intensity and laser scanning speed plays a crucial part in an efficient manufacturing process[4].

Hence, we study the effect of laser parameters, laser intensity, laser scanning speed and spot size.

CHAPTER 3

RESULTS AND DISCUSSIONS

3.1 Variation in Laser Intensity:

As explained in the previous chapter, the computational model of 20 x 20 mm plate of thickness 1mm is validated. In this case, the simulation was carried out for 0.1s. The other parameters, spot size and laser scanning speed were kept constant. Results are discussed for the intensity of 2000, 3500, 10000 W/mm^2. The figure shown below showed the temperature distribution across the thickness and radial temperature variation. All the results shown are at the centre of the laser path.

1) For 2000 W/mm^2 Intensity

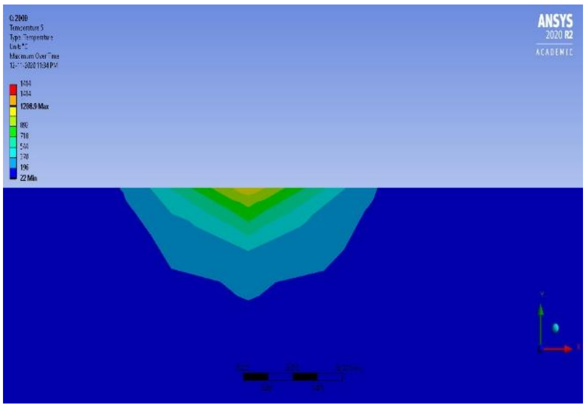


Fig 3.1 Temperature distribution along the thickness 2000 W/mm^2

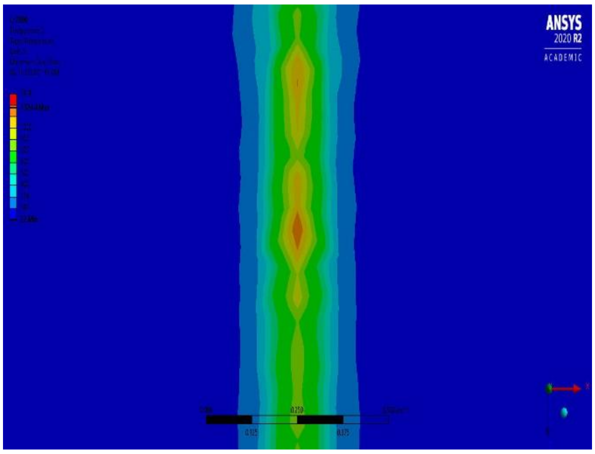


Fig 3.2 Maximum temperature distribution across the surface for 2000 W/mm^2

2) For Intensity of 3500 W/mm^2

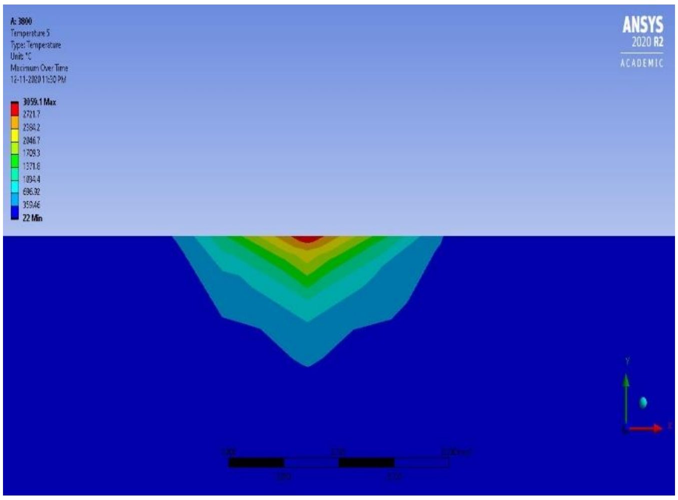


Fig 3.3 Temperature distribution along thickness for 3500 W/mm^2

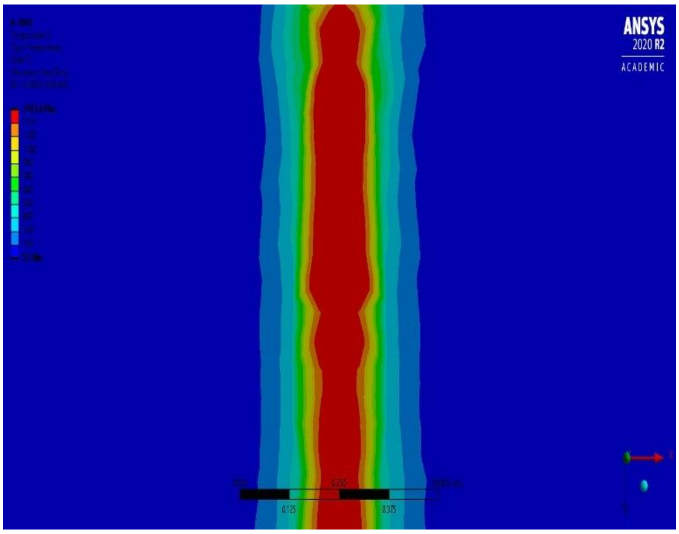


Fig 3.4 Maximum temperature distribution across the surface 3500 W/mm^2

3) For the intensity of 10000 W/mm^2

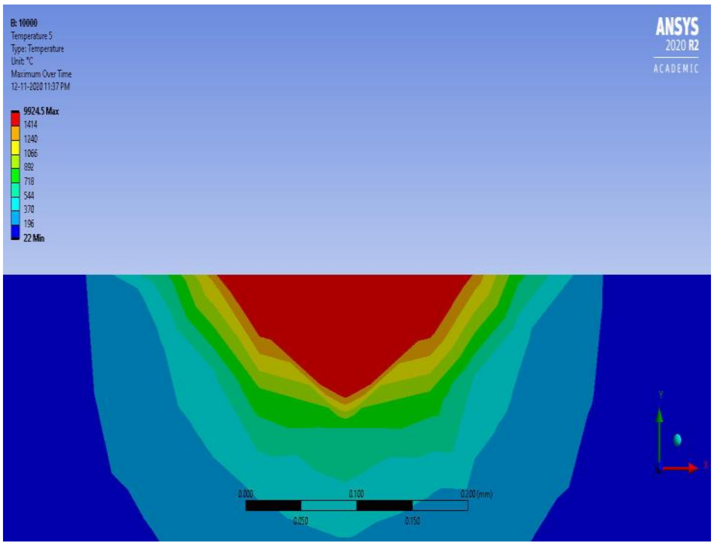


Fig 3.5 Temperature contour along thickness for 10000 W/mm^2

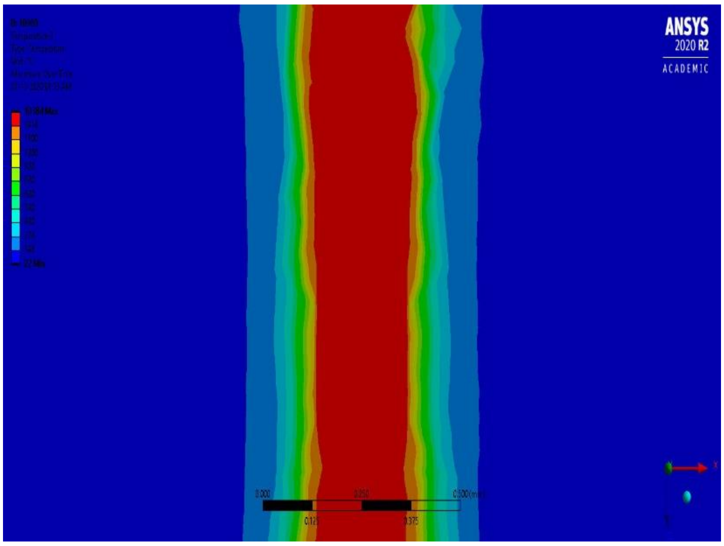


Fig 3.6 Maximum temperature distribution across the surface 10000 W/mm^2

As seen from the simulation results above we can see the difference in the temperature distribution across the thickness and radially for each intensity case. With the increase in intensity maximum temperature achieved is increased. The temperature bar on the simulation image represents the temperature range. The red band of the contour represents the region of the material above the melting temperature of the silicon, which is 1414 °C. In the above simulation results, we can see melting temperature is not achieved in 2000 W/mm^2 case. As we discussed in the above chapter, no etching will be observed as melting temperature is not achieved. While for the intensity of 10000W/mm^2 maximum temperature is very high. As well as the melting temperature reached below the surface is more than the desired etching depth. In the case of 3500 W/mm^2 maximum depth of melting temperature is in good agreement with desired etching depth. Temperature Distribution across the thickness and radially is explained below.

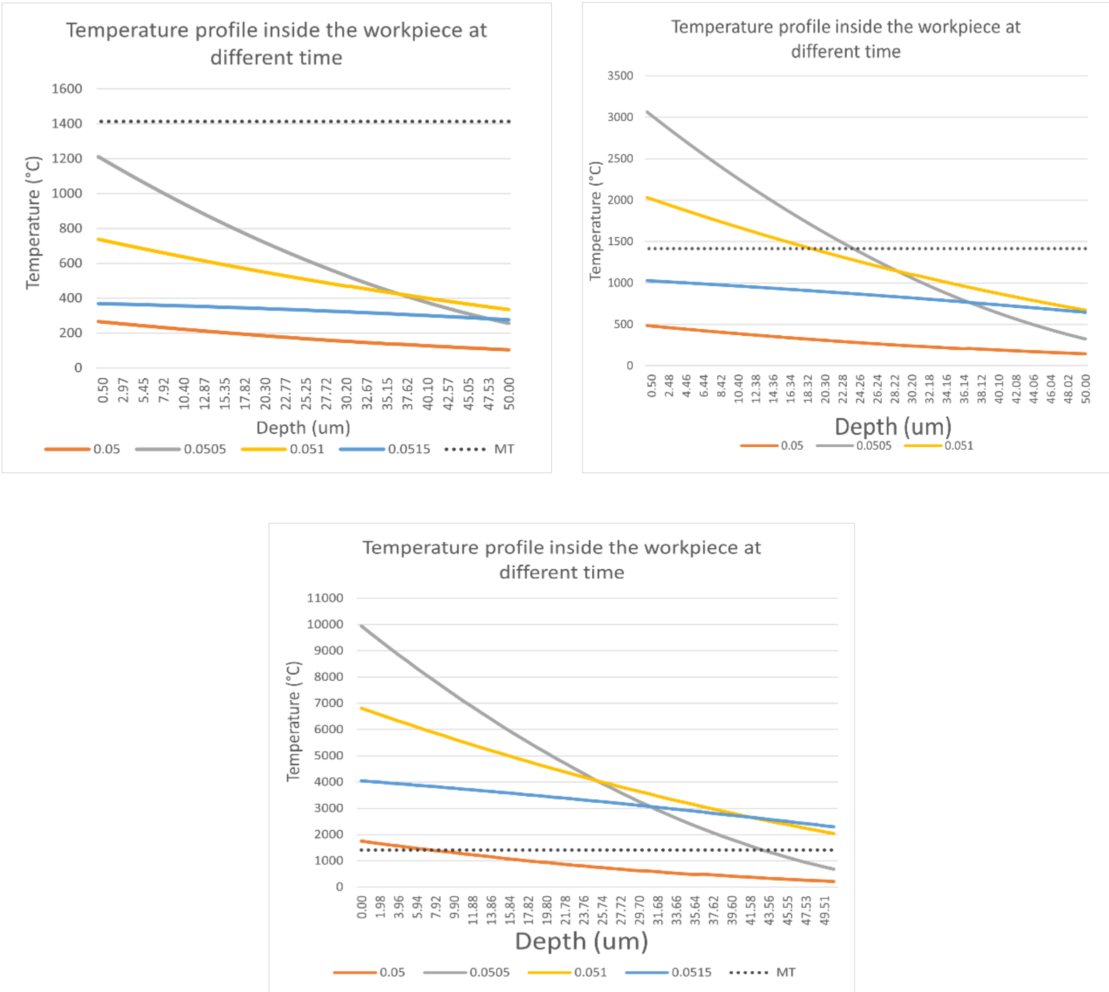


Fig 3.7 Comparison of temperature profile inside the workpiece at a different time for all intensities

The graphs above show temperature variation below the surface at different time. From the above comparison, for 3500W/mm^2 intensity depth achieved is in good agreement with the desired etching depth of 30µm. With an increase in laser intensity, we can see that depth at which melting temperature achieved below the surface increases. This can be used to determine the intensity to be used for etching to get the required etching depth.

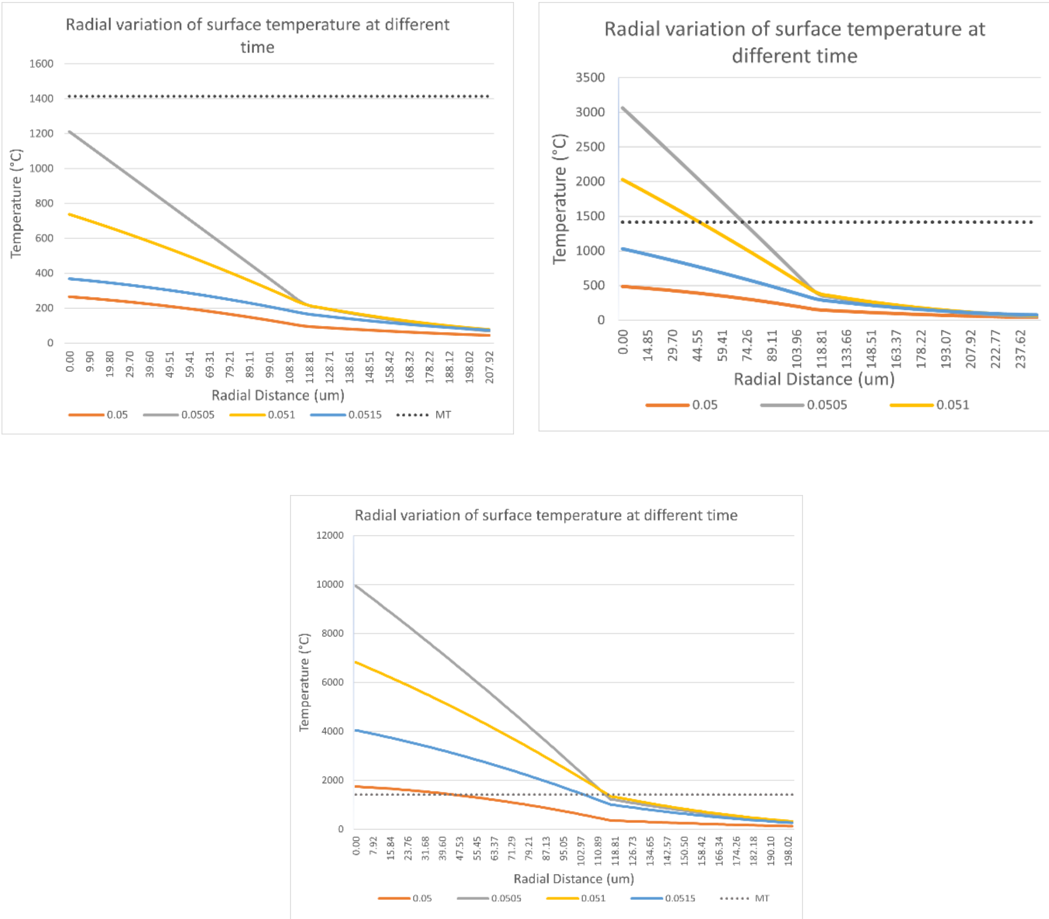


Fig 3.8 Comparison of radial variation of surface temperature at a different time for all intensities

Above graph shows how the temperature varies along the surface of the plate as a time variable. Higher laser intensities produce higher surface temperatures. As we go on increase the laser intensity the width of the melt zone increases. It can be also seen that radial temperature decays sharply. A major portion of the evaporation occurs within the region represented by the red band in simulation results above. This result can be crucial in deciding the width and depth of the etch.

3.2 Variation in Laser scanning speed

In this simulation laser scanning speed is varied. The other parameters, Laser spot size and laser intensity were kept constant. Results are studied for 50, 200 and 500mm/s . All the results shown are at the centre of the laser path. The figure shown below showed the temperature distribution across the thickness and radial temperature variation and the nature of the spot size.

1) For 50 mm/s speed

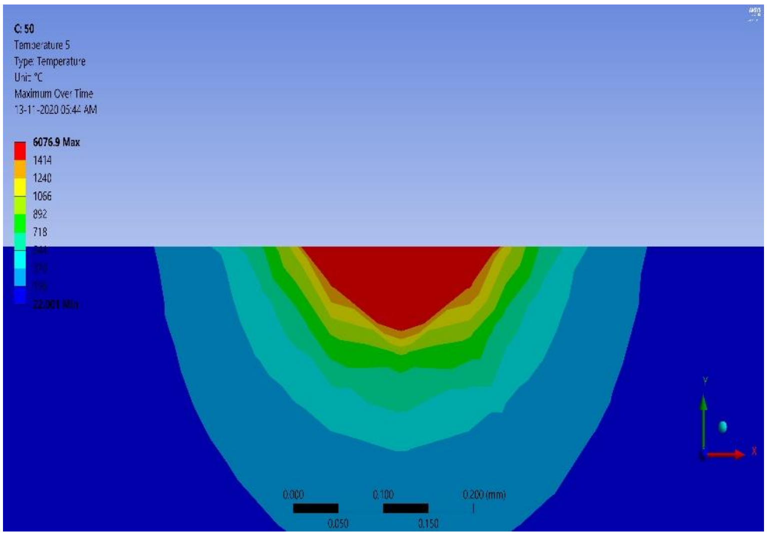


Fig 3.9 Temperature distribution along the thickness for 50 mm/s

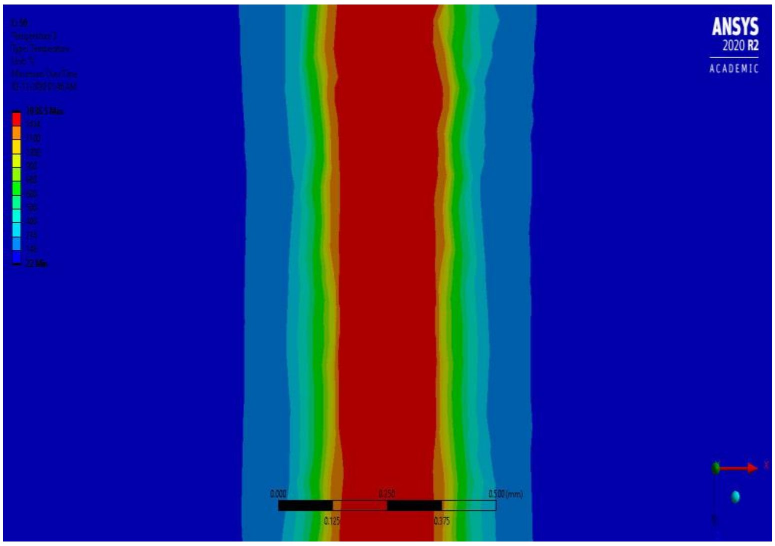


Fig 3.10 Maximum temperature distribution across the surface for 50mm/s

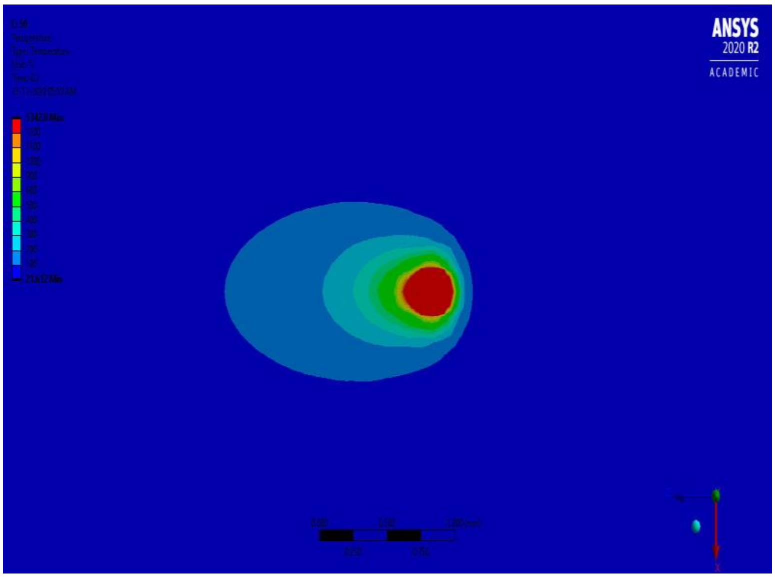


Fig 3.11 Nature of the moving laser spot for 50mm/s

2) For 200 mm/s scanning speed

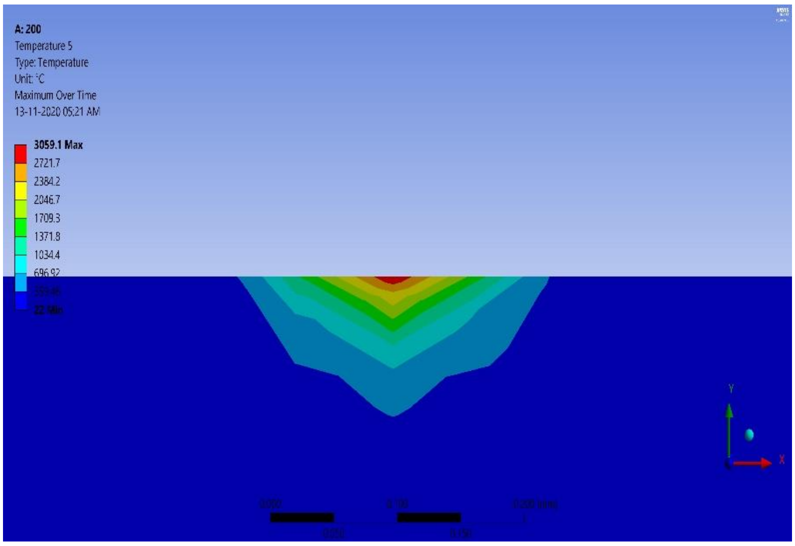


Fig 3.12 Temperature distribution along the thickness 200 mm/s

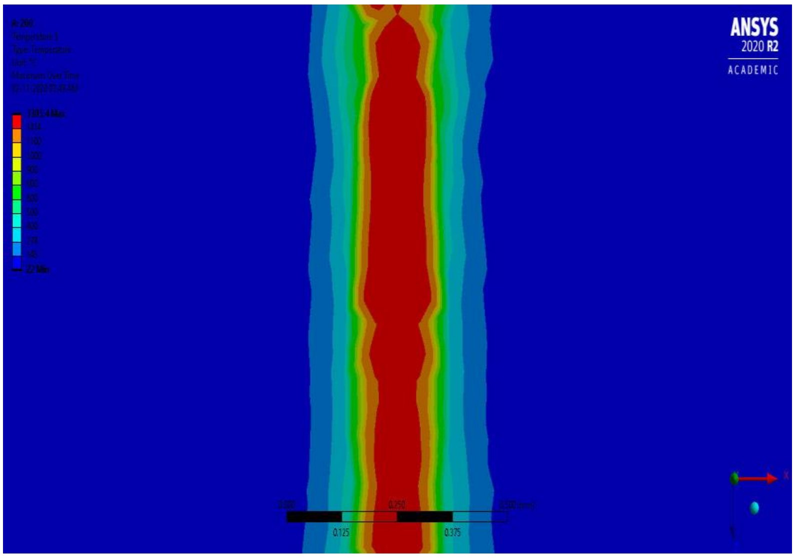


Fig 3.13 Maximum temperature distribution across the surface for 200mm/s

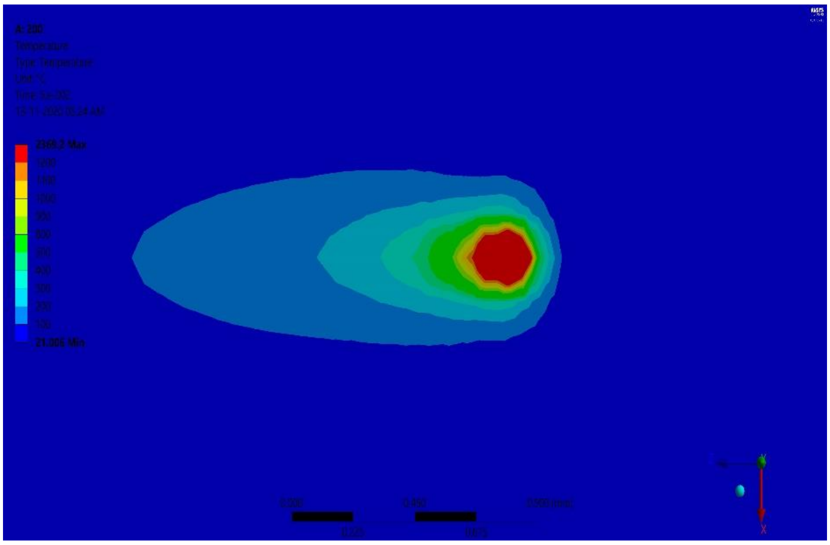


Fig 3.14 Nature of the moving laser spot for 200mm/s

3) For 500 mm/s

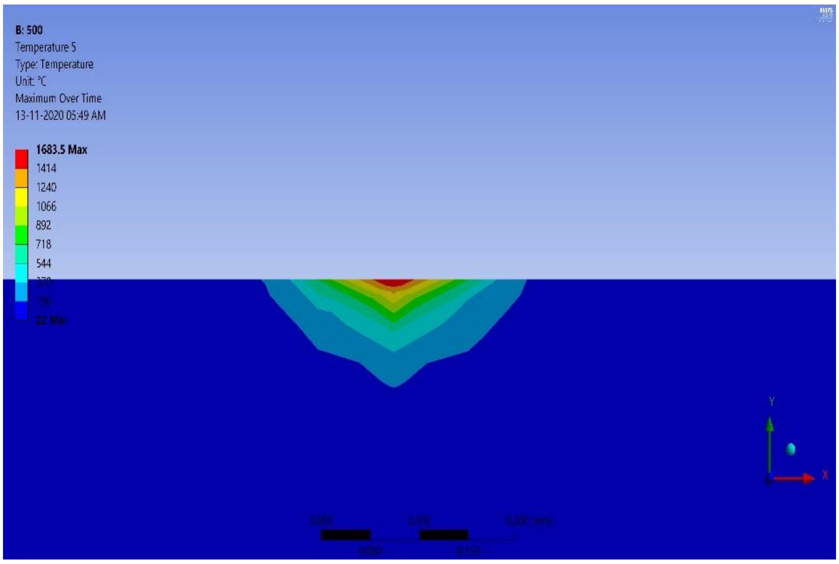


Fig 3.15 Temperature distribution along the thickness 500 mm/s

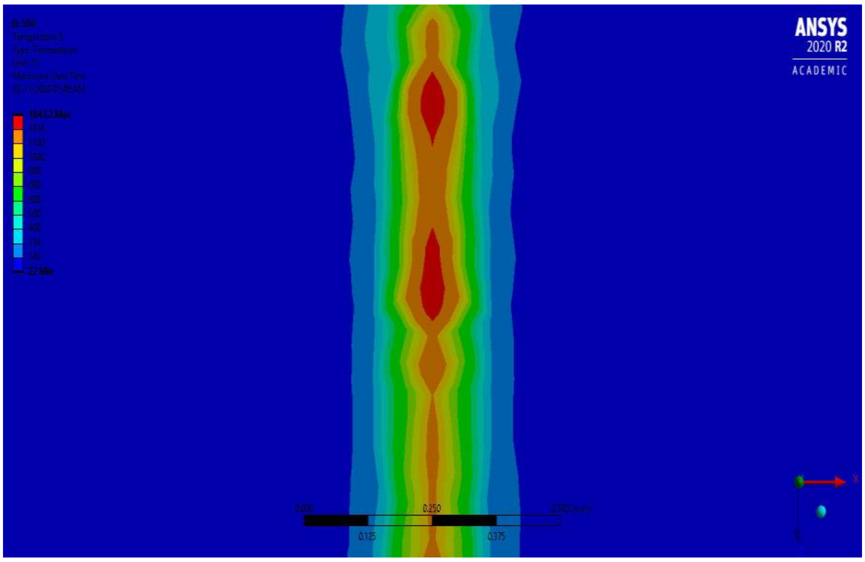


Fig 3.16 Maximum temperature distribution across the surface for 500mm/s

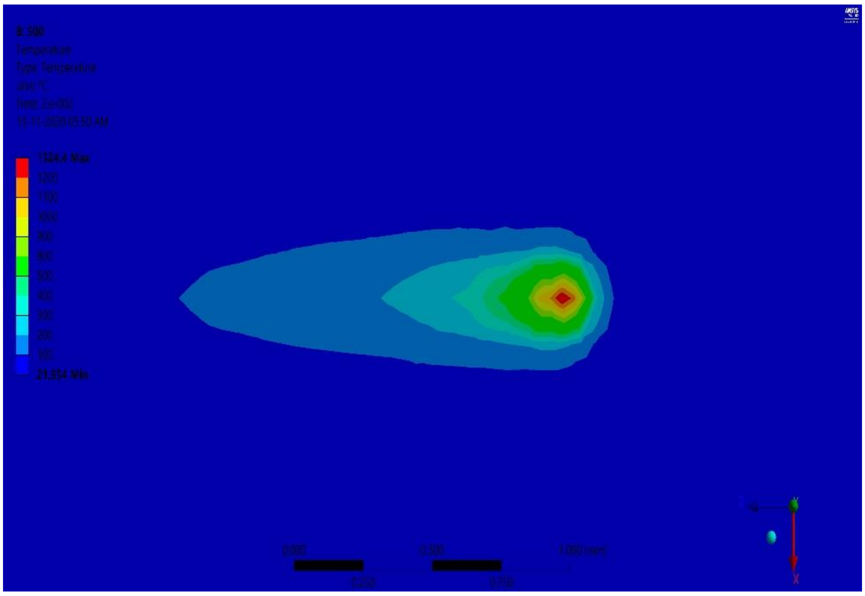


Fig 3.17 Nature of the moving laser spot for 500mm/s

Above simulation results shows the temperature distribution across the thickness and radially for 50,200 and 500mm/s. We can see that for slow laser scanning speed temperature reached is higher. This is because for slow scanning speed surface is irradiated for long compared to scanning speed of 200mm/s and 500mm/s. Also, the temperature below surface is higher for 50mm/s. This can lead to a cut-through hole in the material or wider etching in case of the letter to be etched on the IC package.

We can see the nature of moving laser spot for 50, 200 and 500 mm/s. For high scanning speed of 500mm/s, the shape of the spot is like a comet with a long tail. As laser scanning speed is fast there is less time for the previous phase to cool down, for that reason we see the long tail shape. But, for high scanning speed material is irradiated for short time, that’s why high temperature is not achieved for 500mm/s. Further, the temperature distribution across the thickness and radially is explained below.

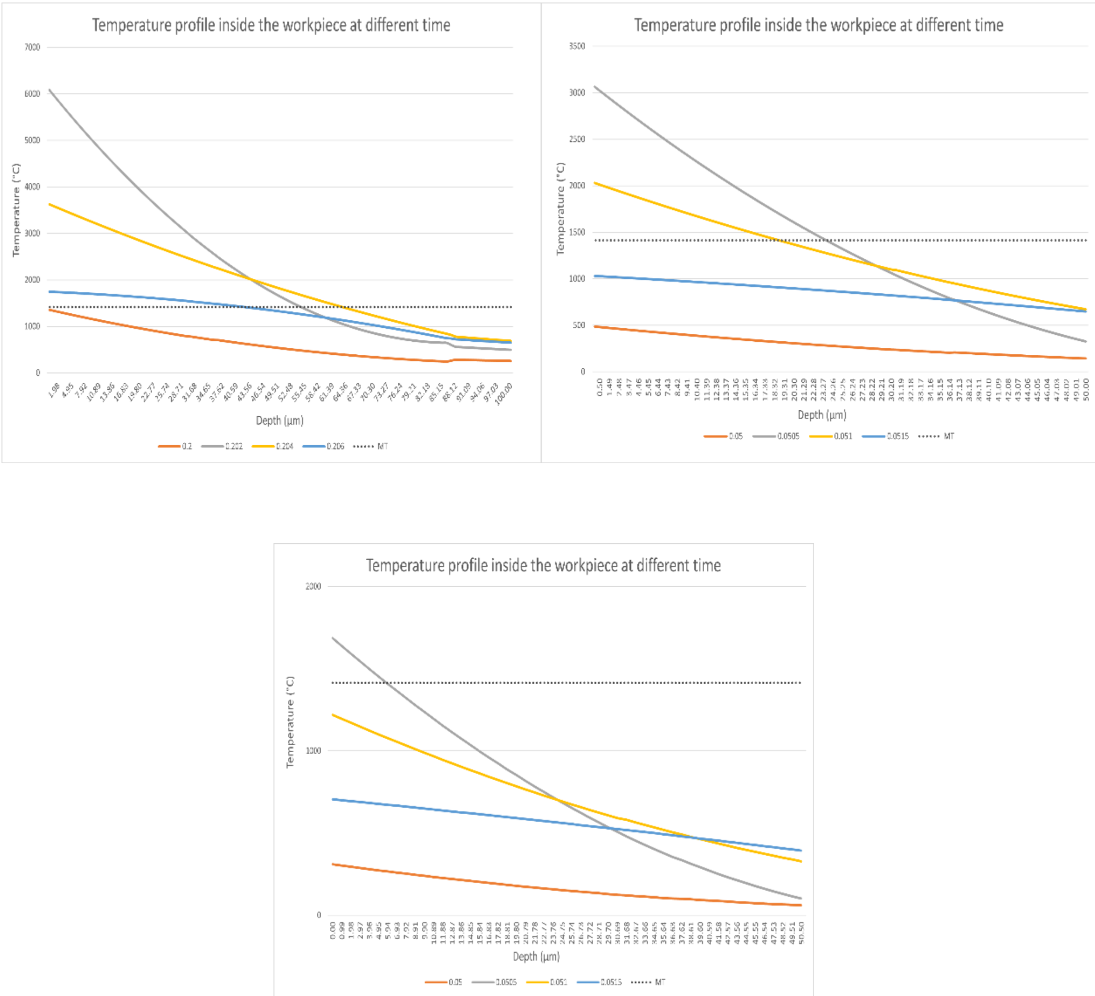


Fig 3.18 Comparison of temperature profile inside the workpiece at a different time for all scanning speeds

Above graph compares the temperature distribution below the material surface. As we can see maximum surface temperature achieved for 50mm/s. Due to slow scanning speed, the material is irradiated for more time and the energy gain by the material surface through absorption is higher. This can lead to higher etching rate or engraving which has more depth than a laser etching process.

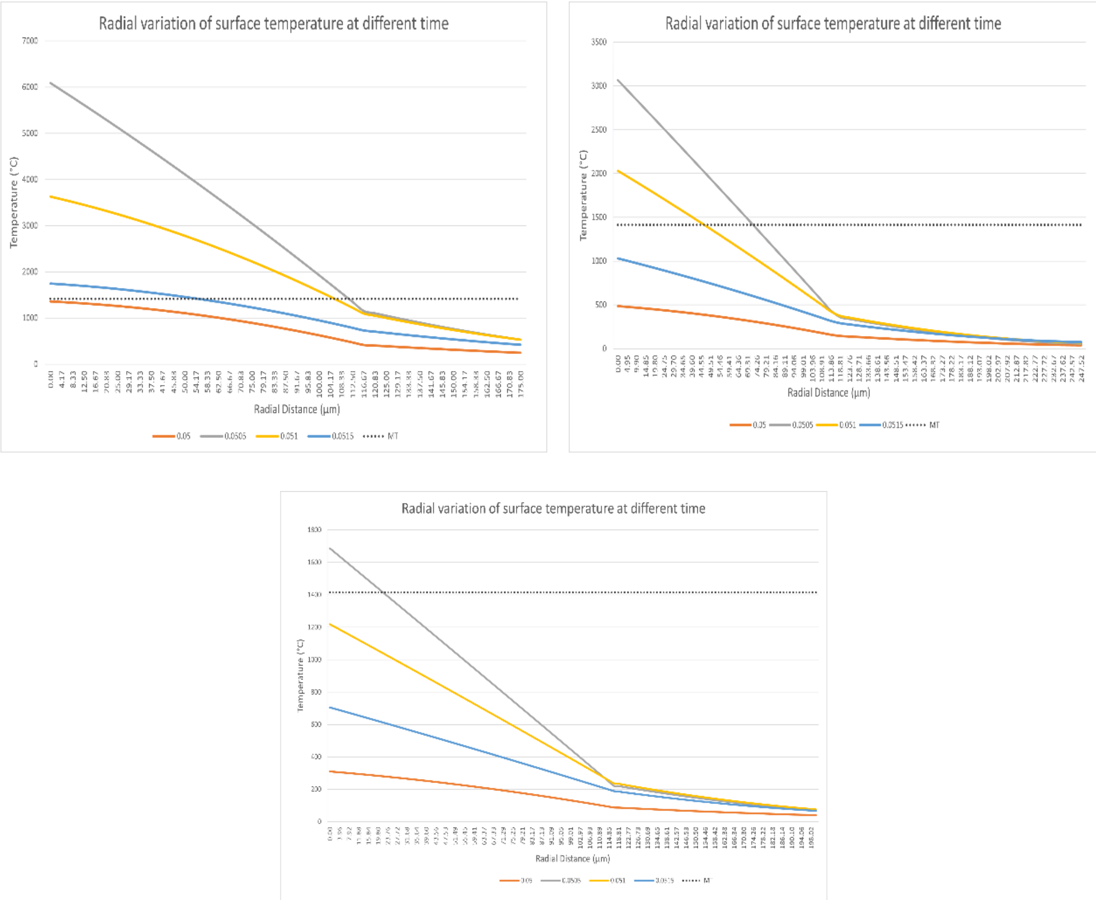


Fig 3.19 Comparison of radial variation of surface temperature at a different time for all scanning speed

Above graph shows surface temperature variation. The graph shows that with an increase in scanning speed the surface temperature decreases. Also, with an increase in scanning speed the width of the melt pool decreases.

3.3 Variation in Laser spot size

For this simulation variation, the laser spot is studied. The other parameters, Laser spot scanning speed and laser intensity were kept constant. Results are studied for 0.05, 0.08 and 0.15mm spot radius. All the results shown are at the centre of the laser path. The figure shown below showed the temperature distribution across the thickness and radial temperature variation.

1) For spot size of 0.05mm

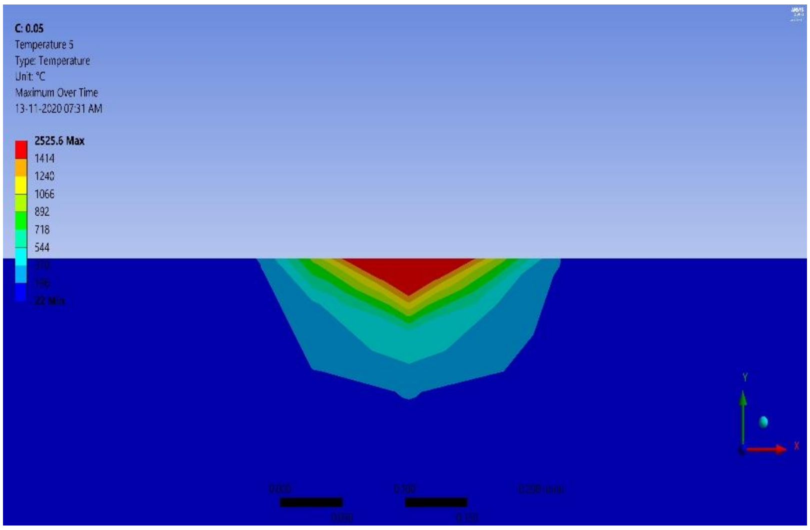


Fig 3.20 Temperature distribution along the thickness 0.05mm

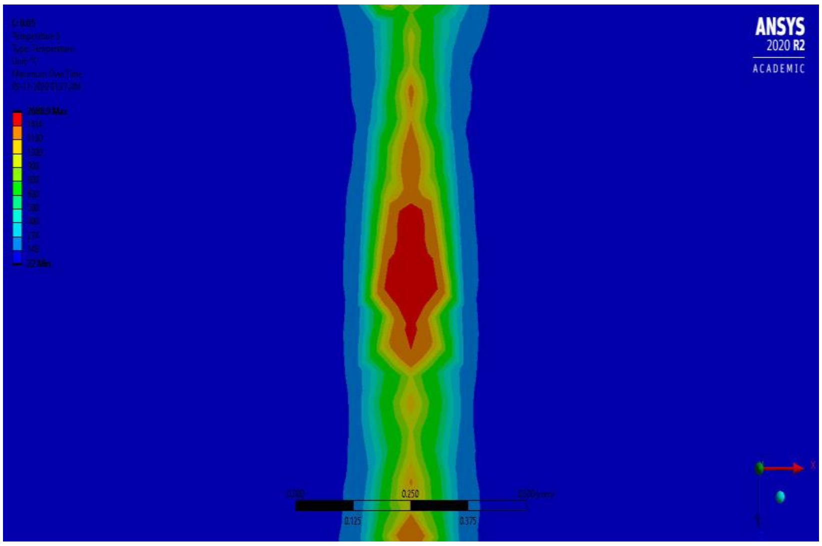


Fig 3.21 Maximum temperature distribution across the surface for 0.05mm

2) For 0.08mm Spot size

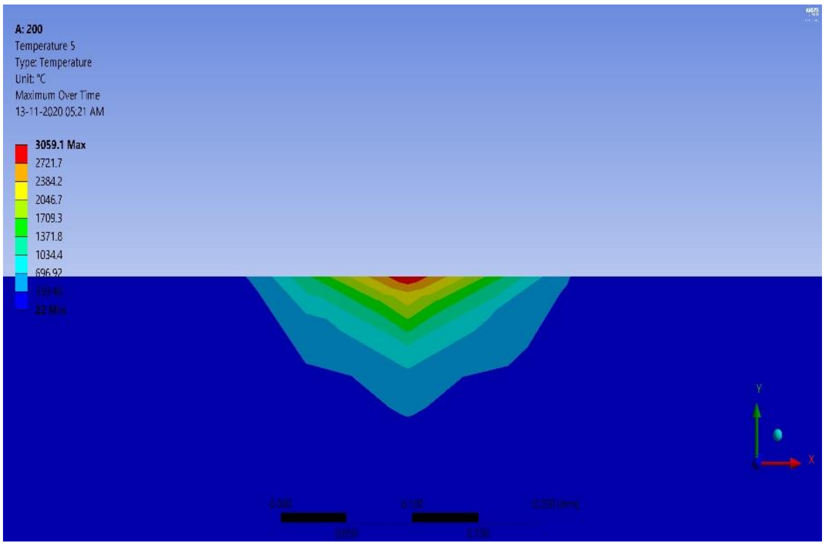


Fig 3.22 Temperature distribution along the thickness 0.08mm

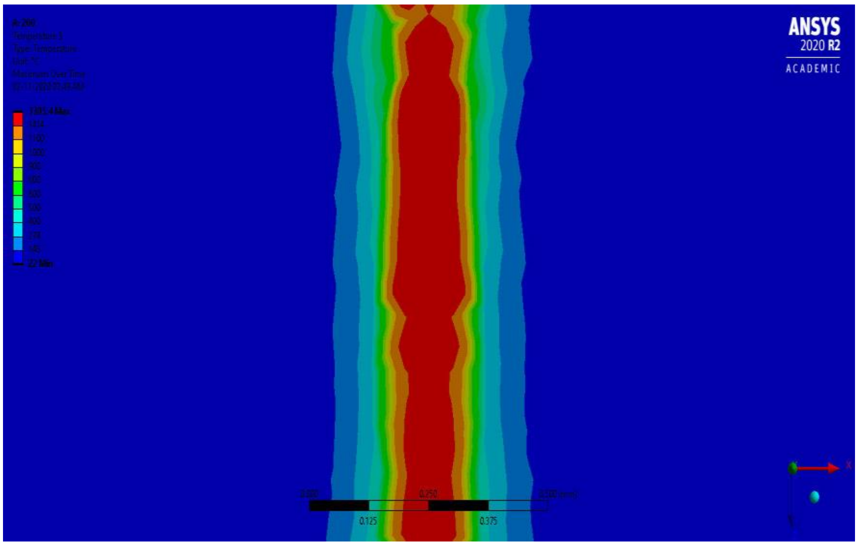


Fig 3.23 Maximum temperature distribution across the surface for 0.08mm

3) For spot size of 0.15mm

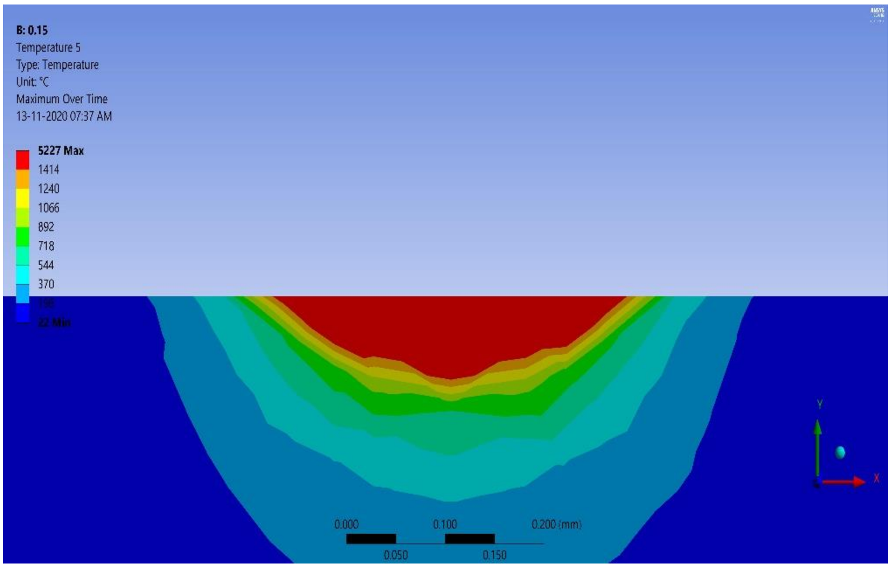


Fig 3.24 Temperature distribution along the thickness 0.15mm

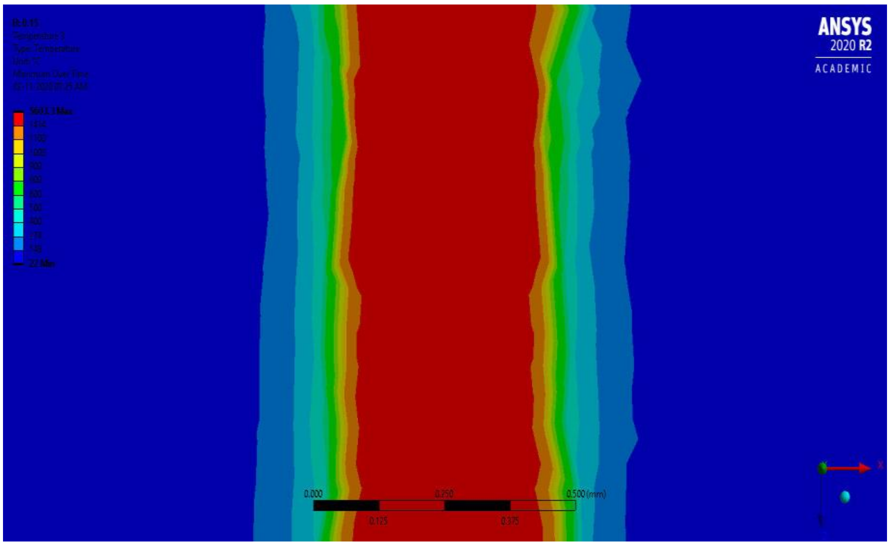


Fig 3.25 Maximum temperature distribution across the surface for 0.15mm

Above Temperature contour shows the temperature distribution across the thickness and radially for a spot size of 0.05, 0.08 and 0.15mm radius. The simulation shows that with increase with spot size surface temperature increases. Melt pool width also increases with the increase in spot size radius. Significantly less or no etching can be seen for a 0.05mm spot size radius. While for 0.15mm spot size radius depth of etching achieved is more than the desired etching depth. Temperature distribution across the thickness and radially is explained below.

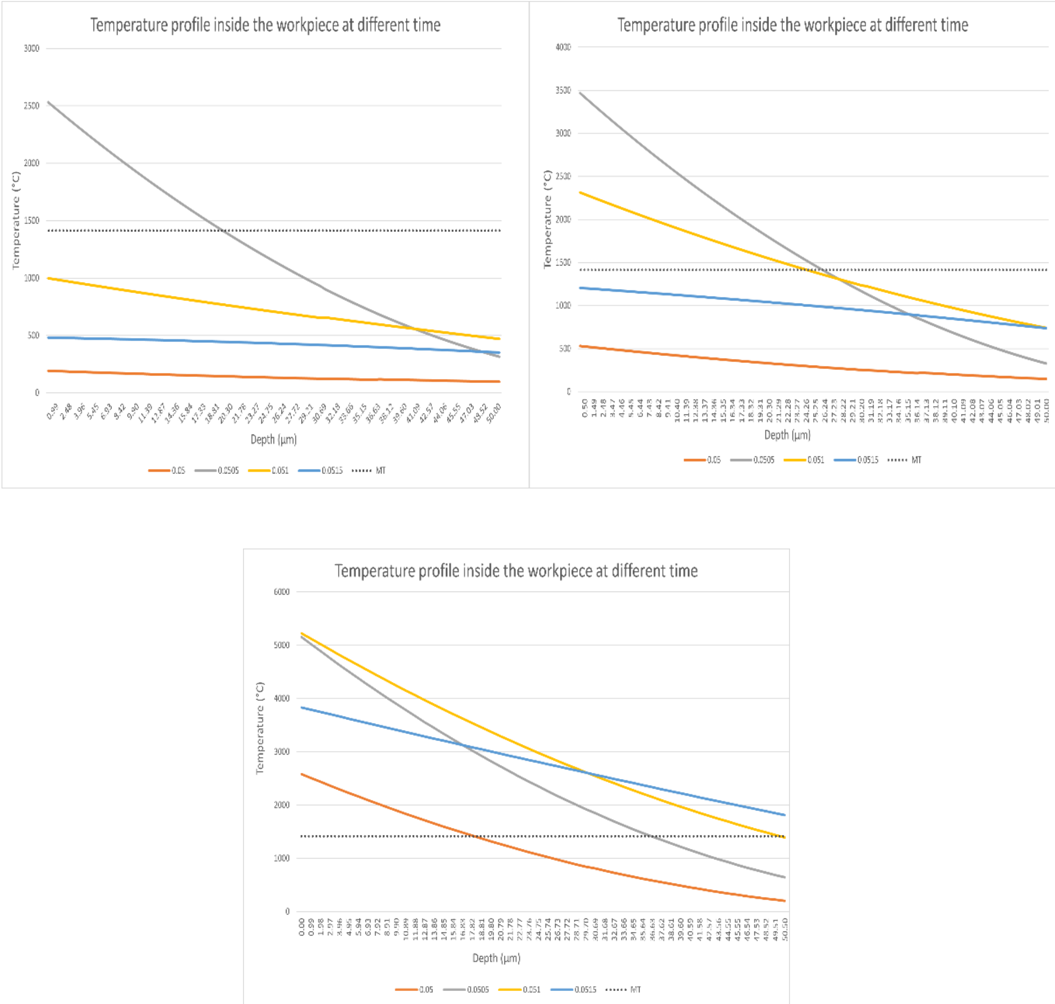


Fig 3.26 Comparison of temperature profile inside the workpiece at a different time for all spot size radius

Above comparison shows that temperature profile below the surface at different time. As we can see for 0.08mm maximum depth below the surface where melting temperature is observed is 25µm, which is in good agreement with the desired etching depth. While for depth achieved for 0.15mm is very high for laser etching process.

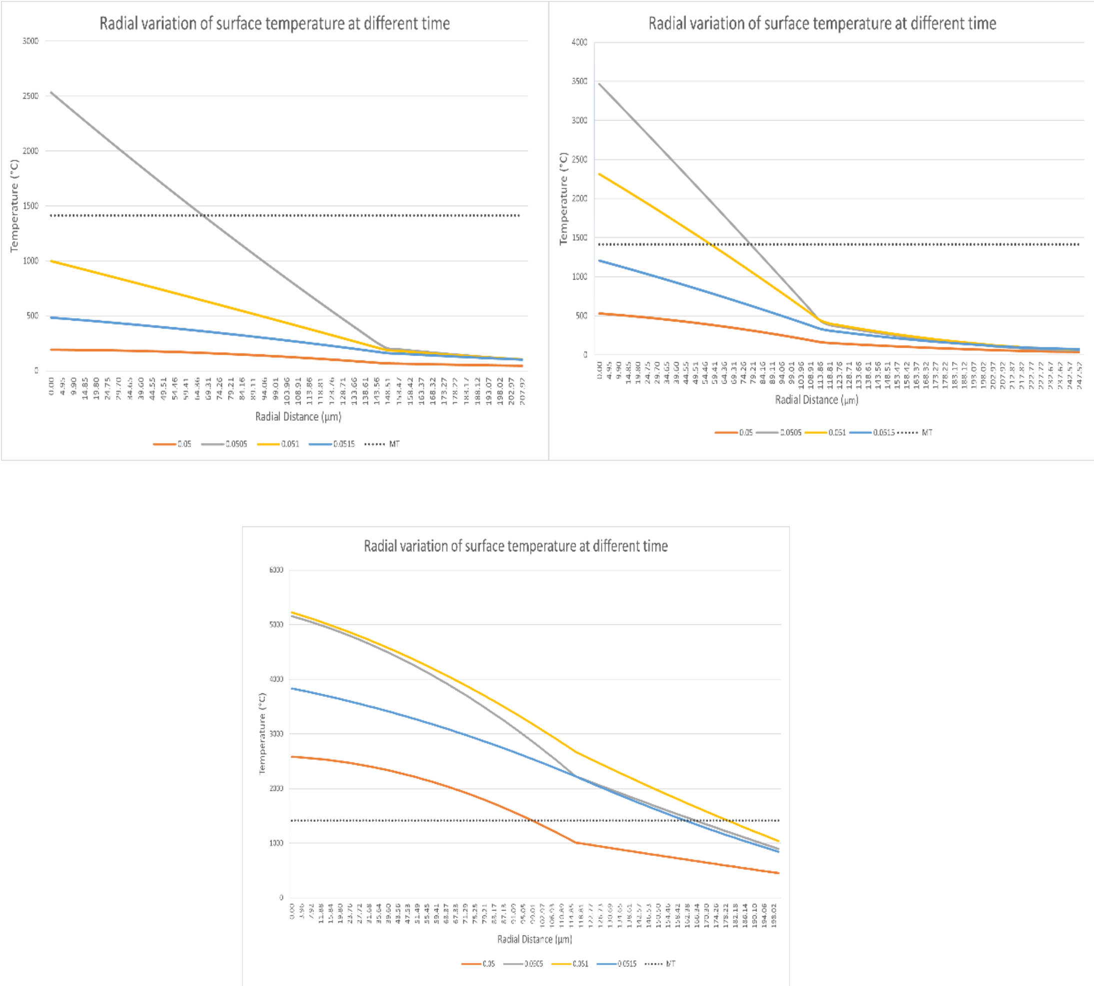


Fig 3.27 Comparison of radial variation of surface temperature at a different time for all spot size radius

Graphs show the temperature distribution along the surface of the material. For spot size of 0.15mm width of melt pool is wider than for spot size of 0.05mm and 0.08mm. As laser spot size bigger in case of 0.15mm, more laser beam energy is irradiated on the material surface, which results in higher temperature. We can see from the graph that with an increase in laser spot size radius width of the melt pool increases.

CHAPTER 4

CONCLUSION

This research reviews the computational study of parameters of a laser etching process. The finite element analysis approach is introduced using ANSYS workbench to solve the problem. The conclusions from the present study can be listed as follows:

1. Effect of Laser Intensity on the laser etching process

Variation in laser intensity is investigated for the laser etching process on a silicon plate of 1mm thickness. Increasing the laser intensity from 2000 W/mm^2 to 10000W/mm^2, the surface temperature increased. Also, the depth of etching increases with an increase in laser intensity. While at 10000W/mm^2 laser intensity can result in a deep cut or cut through-hole which is not the objective of the laser etching process. On the other hand, at a low laser intensity of 2000 W/mm^2 can result in no etching as melting temperature not achieved. Also, the width of the melt pool increases with an increase in intensity. Thus, to get the desired etching depth on the material study of laser intensity plays an important role.

2. Effect of Laser scanning speed on the laser etching process

50 mm/s, 200 mm/s and 500 mm/s laser scanning speed are investigated. With a slow-scanning speed of 50mm/s, high temperature can be achieved which can result in a high etch rate. But very slow scanning speed results in cut through and wide melt pool. While fast scanning speed of 500mm/s can result in no etching as the material is irradiated by a laser beam for short time.

3. <u>Effect of laser spot size on the laser etching process</u>

Variation in spot size radius is investigated. The higher temperature is achieved with an increase in laser spot size. For large laser spot size of 0.15mm area irradiated by the laser beam is more which can result in the wide melt pool. Hence, Laser spot size is crucial in letter etching on the material.

CHAPTER 5

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