Thermal Modelling for Laser Machining of SS316 L, Inconel 718 and Ti6Al4V

Ganesh Dongre¹, Avadhoot Rajurkar¹, Akash Haria¹, Abhilash Kulkarni¹, Ravi Raut¹

¹Department of Industrial & Production Engineering, Vishwakarma Institute of Technology, Pune

Email: ganesh.dongre@vit.edu, avadhoot.rajurkar@vit.edu, akash.haria@vit.edu, abhilash.kulkarni@vit.edu, raviaraut@vit.edu

Abstract. Laser beam machining is a complex thermal process of material removal. In this process, thermal energy is used to vaporize and remove the material from a particular area. Hence a comprehensive study is needed to completely understand the process which can be achieved by a simulation model and its validation through experimentation. In this paper this was achieved with an experimental study to see the relation between the Laser power and the material removal rate (MRR) of SS 316 L, Inconel 718 and Ti6Al4V during the process of Laser Machining. Also a 3D transient model of a moving Gaussian heat source was developed in ANSYS 18.2 to predict the MRR for different values of laser power. Mesh sensitivity analysis was done prior to the usage of the model so as to choose the perfect mesh size which can give the best results possible. After validation of the model, a close correlation was found between the experimental data and the simulation results. In the simulation model it was also observed that the temperature is maximum at the point of contact of the laser and is comparatively very high for a fraction of second.

Keywords: Thermal Modelling, Simulation Model, MRR, Laser Machining.

1. Introduction
The special nature of LASER light acronym for Light Amplification by Stimulated Emission of Radiation, a scientific discovery of the 20th century, has made laser technology a vital tool in nearly every aspect of everyday life. Laser is nowadays used in vast and various applications like entertainment, electronics, information technology, material processing, medical and military devices. In case of material processing, it is used in processes like Selective Laser Sintering, Laser Beam Machining, Laser Micro Drilling, etc. Various laser applications in Industry are shown in a pie chart in Fig. 1. Laser machining has many advantages over conventional machining techniques in terms of precision, machining time, intricacy of shapes etc. Even though it has many pros, it also has some cons like higher cost of operation, difficult for mass metal processes, highly trained individuals required, etc. Taking into account the disadvantage of higher cost of operation, it can be reduced if in some way we can predict the outcome of the machining process without actually carrying out the process. This is possible by simulation of the laser machining processes. There are many software’s available in the market for developing such simulation models. In this paper, ANSYS 18.2 is used to simulate the laser machining
process and to predict the material removal rate of the process and then the model is validated by benchmarking it on a machine 'NUQA 30W' by Coherent Laser.

![Figure 1. Laser Applications in Industry. [13].](image)

2. Literature Review

Jihong Yang et. al.[1], in their paper have studied and investigated the heat affected zone in Ti6Al4V during laser assisted machining using ANSYS. They derived the relation between HAZ with laser power and scan speed. It was observed that with the increase in laser power the HAZ increases and with increase in scan speed of the laser the HAZ decreases.

J.I. Arrizubieta et. al. [2] have developed and validated a simple 3D model which predicts the surface temperatures and thermal fields inside the heated part in a Laser Assisted Turning (LAT) process in their paper. Knowing the thermal fields can help to predict the cutting depth in the component which is practically not possible. The influence of different parameters like laser power, rotation velocity, part size, material conductivity, etc. on the process was also determined.

F. M. Mwema [3], in his paper has developed a transient thermal model for temperature field in laser welding in the software 'SolidWorks'. The results, as expected were that the temperatures at the point of contact were high and reduced as the laser moved forward, except the temperature at the end of the laser movement is higher as compared to the starting point which probably is due to the accumulation of the temperature before arriving at the end. He also concluded that it was difficult to model a moving heat source in SolidWorks and non-linearity of materials cannot be modelled.

A thermal model of laser based additive manufacturing processes was developed and analysed by John Romano et. al. [4]. It was seen that the temperature distributions of various materials during laser machining was different. It showed that more power was needed to maintain melting in steel and aluminium powder beds as compared to titanium powder beds. Also due to the low absorptivity of the powder and high conductivity of the solid it is difficult to initiate and maintain melting in Al powder even though it has the lowest melting point of the three materials.

XueFeng Wu et. al. [5] have created a transient 3D thermal model for a Laser Assisted Milling process (LAML) of Inconel 718. The predicted temperatures of the model were validated by the experimental temperature values. The effects of laser power and laser scan speed were also studied using the same model. The laser power was the most crucial parameter for the change of temperatures during the LAML process.

3. Mesh Sensitivity Analysis

Mesh size and mesh type is one of the most crucial parameters in any simulation model. The results vary to a large extent if the mesh sizes are varied and hence should be varied only in a particular range where
the difference in the results is comparatively low. Therefore, the Mesh Sensitivity can be defined as the amount of change in the results with change in mesh size or type. More the change in results, more sensitive the mesh size will be.

In this case the mesh sizes taken are from 0.06 mm to 0.2 mm due to computational limitations. The mesh type used is a normal cubical mesh type. The following graph was obtained for Material Removal Rate (MRR) and the mesh size ranging from 0.06 mm to 0.2 mm.

Table 1: Data for mesh sensitivity analysis

| Sr. No. | Mesh Size (mm) | Volume Removed (mm³) | MRR (mm³/sec) |
|---------|----------------|----------------------|---------------|
| 1       | 0.06           | 0.0591               | 0.01182       |
| 2       | 0.07           | 0.0509               | 0.01018       |
| 3       | 0.08           | 0.0604               | 0.01208       |
| 4       | 0.09           | 0.0672               | 0.01344       |
| 5       | 0.1            | 0.0588               | 0.01176       |
| 6       | 0.125          | 0.0680               | 0.01360       |
| 7       | 0.15           | 0.0832               | 0.01665       |
| 8       | 0.175          | 0.1068               | 0.02137       |
| 9       | 0.2            | 0.0606               | 0.01212       |

For this, a cuboid was developed in ANSYS. The different mesh sizes from 0.06mm to 0.2mm were given to the cuboids and then accordingly a heat flux was given. Using element birth and death technique the elements with temperature greater than the vaporization temperature were deleted to get the volume and finally get the MRR.

From the graph we can analyse and conclude that:
1) The MRR increases as the mesh size increases up to 0.175 mm. However, after 0.175 mm it starts to decrease.
2) As the mesh size increases from 0.06 mm to 0.125 mm, the change in the results is appreciable.
3) But as the mesh size increases from 0.125 mm to 0.2 mm the change in the results is quite high and is not appreciable.

4. Model Formulation
The following transient 3D thermal model was developed in ANSYS 18.2. The model consists of a cube of dimension 7x7x1 mm whose top surface area of dimension 1.2x1.2 mm is given a moving heat flux with a pulsed time just like a moving pulsed laser.

4.1. Element Type
The element type used for this model is SOLID278. It has eight nodes with a single degree of freedom, temperature, at each node. The element is applicable to a 3-D, steady-state or transient thermal analysis.

4.2. Gaussian Heat Source
A Gaussian heat source which is most widely used model is used in this case. In case of a Gaussian heat source the power per unit area is maximum at the centre of the beam and is symmetric about their propagation direction. The beam power at any point is given by the equation [14].

\[ I(x, y) = \frac{2 \cdot P}{\pi \sigma^2} \exp\left[ -\frac{2(x^2 + y^2)}{\sigma^2} \right] \]

Where, \( P \) = laser power, \( \sigma \) = radius, \( I \) = Intensity of gaussian heat source.

4.3. Conduction Equation
During any laser machining operation, the thermal field is governed by the following conduction equation [16].

\[ \frac{\partial}{\partial x} \left( k(T) \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k(T) \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( k(T) \frac{\partial T}{\partial z} \right) + Q_z = \rho(T) C_p(T) \frac{\partial T}{\partial t} \]

Where, \( T \) is the temperature, \( k(T) \) is the thermal conductivity, \( \rho(T) \) is the specific mass, \( C_p(T) \) is the specific heat and \( Q_v \) is the volumetric heat flux.

4.4. Convection Equation
Convection is the transfer of heat from one place to another by the movement of fluids. In the current model we have applied the convection effect on the top surface of the cube where the melting of the metal occurs. The equation of convection [17] is given as follows.

\[ q = h(T_{hot} - T_{cold}) A \]

Where, 'q' is the heat transferred per unit time, 'A' is the area of the object, 'h' is the heat transfer coefficient, \( T_{hot} \) = Temperature of hotter material, \( T_{cold} \) = Temperature of cold material.
4.5. Perfectly Insulated Areas

All the faces except the top face of the cube in this simulation model have been applied with a boundary condition of perfectly insulation. This is due the fact that when an object is heated the heat dissipation occurs to the surrounding environment because of radiation. To avoid the dissipation of heat this boundary condition is crucial in this simulation model.

![Perfectly Insulated Areas Diagram](image)

**Figure 4.** Workpiece with boundary conditions.

4.6. Element Birth And Death

The element birth and death options can be used to deactivate or reactivate selected elements in the model. It is generally used to deactivate elements when a certain load is not to be applied on that element for a particular amount of time. In this case this technique is used to delete the elements which have a temperature of 31000 K or higher that is the vaporization temperature. So when the elements are deleted or rather deactivated, we can get the volume of the elements which are deactivated and hence we can get the mass of the material removed and further MRR can be calculated from the simulation model.

5. Model Input Parameters

| Sr. No. | Parameter          | Value                                           |
|---------|--------------------|-------------------------------------------------|
| 1       | Thermal Conductivity | SS316: 17 W/mK, Inconel: 11.3W/mK, Ti6Al4V: 6.7W/mK |
| 2       | Specific Heat      | SS316: 530 J/KgK, Inconel: 435J/KgK, Ti6Al4V: 527 J/KgK |
| 3       | Density            | SS316: 7800 kg/m$^3$, Inconel: 8200 kg/m$^3$, Ti6Al4V: 4430 kg/m$^3$ |
| 4       | Laser Beam Diameter | 19µm                                           |
| 5       | Melting Temperature | SS316: 1800K, Inconel: 1673K, Ti6Al4V: 1940K  |
| 6       | Vaporization Temperature | SS316: 3100K, Inconel: 2950K, Ti6Al4V: 3300K |
| 7       | Time of Simulation | 60 secs                                        |
| 8       | Workpiece Dimension | 30x30x1mm                                      |

5.1. Simulation Results
6. Experimental Plan And Procedure

The experiments for the validation of the simulation model were carried out on a NUQA 30W Fiber Laser Machine by Coherent Laser. The type of Laser used in this machine is a Diode Pump Fiber Laser with a maximum Laser Power of 30W. The following procedure was used to carry out the experiment.

6.1. Work Piece Preparation
Firstly big sheets of SS316 L, Inconel 718 and Ti6Al4V of thickness 1mm were cut into 30 equal pieces of dimension 30*30mm. The work pieces thus obtained were then grinded and polished to get a smooth surface and to remove any burrs. A belt grinder was used for grinding and polishing papers of grade 4 to grade 0 were used for polishing of the specimens.

6.2. Weighing Of The Specimens
Since the objective of work is to find out the material removal rate (MRR) of the laser machining process, knowing the change in weight of the specimen after machining as compared to the weight before machining will help to calculate the MRR. In general, MRR is defined as the weight of the material removed per minute. Hence the experimental process and the simulation model both are carried out for 60 secs that is 1 min. So, before the machining is carried out, all the specimens are to be weighed precisely as the material removed will be in milligrams.

6.3. Experimentation
The above prepared specimens were then machined on the Fiber Laser Machine. A square of size 1.2x1.2mm was given as an input to be machined on the top surface of the work piece. The following parameters were given while machining of the work piece.

| Table 3: Parameters of the Machine fixed for our experiment. |
| Sr. No. | Parameter                | Value   |
|---------|--------------------------|---------|
| 1       | Frequency                | 60 KHz  |
| 2       | Speed of the Laser       | 150mm/sec |
| 3       | Time of Machining        | 60 secs |
| 4       | Hatching Pattern         | Cross   |
| 5       | Line Spacing             | 5µm     |

Six different laser power values i.e. 11.2, 12.6, 14, 15.4, 16.8, 18.2 Watts were used for different specimens. To ensure the repeatability factor, the above procedure was repeated 5 times and the results of best 3 experiments were taken for further calculation of error bars.

6.4. Calculation Of MRR

After the above experimentation, there is a void created in the specimens of almost the size of the square that is 1.2x1.2 mm. So clearly some of the metal is vaporized and hence the weight of the specimens has to change. Hence these specimens were weighed and the change in the weights of the specimens as compared to the earlier weight values were noted down and then analysed.

7. Results And Discussions

Table 4: Experimental results and Simulation Results of SS316

| Power (Watt) | MRR ANSYS (gm/min) | MRR Actual 1 (gm/min) | MRR Actual 2 (gm/min) | MRR Actual 3 (gm/min) |
|--------------|---------------------|-----------------------|-----------------------|-----------------------|
| 11.2         | 0.004621            | 0.0024                | 0.0026                | 0.0041                |
| 12.6         | 0.0063              | 0.0042                | 0.0042                | 0.0042                |
| 14           | 0.0063              | 0.0037                | 0.0060                | 0.0044                |
| 15.4         | 0.007138            | 0.0043                | 0.0056                | 0.0043                |
| 16.8         | 0.009               | 0.0048                | 0.0072                | 0.0045                |
| 18.2         | 0.00975             | 0.0066                | 0.0079                | 0.0052                |
### Table 5: Error Graph Values of SS316

| AVG (gm/min) | MIN (gm/min) | MAX (gm/min) | Positive Error Value | Negative Error Value |
|--------------|--------------|--------------|----------------------|----------------------|
| 0.00303      | 0.0024       | 0.0041       | 0.00106              | 0.00063              |
| 0.0042       | 0.0042       | 0.0042       | 0.0013               | 0.001                |
| 0.0047       | 0.0037       | 0.006        | 0.00086              | 0.00043              |
| 0.00473      | 0.0043       | 0.0056       | 0.0017               | 0.001                |
| 0.0055       | 0.0045       | 0.0072       | 0.00133              | 0.00136              |
| 0.00656      | 0.0052       | 0.0079       |                      |                      |

### Table 6: Experimental results and Simulation results of Inconel 718

| Power (Watt) | MRR ANSYS (gm/min) | MRR Actual 1 (gm/min) | MRR Actual 2 (gm/min) | MRR Actual 3 (gm/min) |
|--------------|---------------------|------------------------|-----------------------|------------------------|
| 11.2         | 0.00308             | 0.0025                 | 0.0034                | 0.0041                 |
| 12.6         | 0.003975            | 0.0037                 | 0.0049                | 0.0057                 |
| 14           | 0.00485             | 0.0042                 | 0.005                 | 0.0058                 |
| 15.4         | 0.00625             | 0.0047                 | 0.0051                | 0.0061                 |
| 16.8         | 0.007508            | 0.0049                 | 0.0056                | 0.0071                 |
| 18.2         | 0.008308            | 0.0059                 | 0.0056                | 0.0069                 |

### Table 7: Error Graph Values of Inconel 718

| AVG (gm/min) | MIN (gm/min) | MAX (gm/min) | Positive Error Value | Negative Error Value |
|--------------|--------------|--------------|----------------------|----------------------|
| 0.00333      | 0.0025       | 0.0041       | 0.00076              | 0.00083              |
| 0.00476      | 0.0037       | 0.0057       | 0.00093              | 0.00106              |
| 0.0055       | 0.0042       | 0.0058       | 0.0008               | 0.0008               |
| 0.0053       | 0.0047       | 0.0061       | 0.0008               | 0.0006               |
| 0.00586      | 0.0049       | 0.0071       | 0.00123              | 0.00096              |
| 0.00613      | 0.0056       | 0.0069       | 0.00076              | 0.00053              |

### Table 8: Experimental Results and Simulation Results of Ti6Al4V

| Power (Watt) | MRR ANSYS (gm/min) | MRR Actual 1 (gm/min) | MRR Actual 2 (gm/min) | MRR Actual 3 (gm/min) |
|--------------|---------------------|------------------------|-----------------------|------------------------|
| 11.2         | 0.002661            | 0.0016                 | 0.001                 | 0.0024                 |
| 12.6         | 0.003628            | 0.0021                 | 0.0029                | 0.0027                 |
| 14           | 0.004112            | 0.0022                 | 0.0031                | 0.0029                 |
| 15.4         | 0.004112            | 0.0023                 | 0.0032                | 0.0037                 |
| 16.8         | 0.005201            | 0.0027                 | 0.0037                | 0.0041                 |
| 18.2         | 0.005685            | 0.0031                 | 0.0044                | 0.0044                 |

### Table 9: Error Graph Values of Ti6Al4V

| AVG (gm/min) | MIN (gm/min) | MAX (gm/min) | Positive Error Value | Negative Error Value |
|--------------|--------------|--------------|----------------------|----------------------|
| 0.00166      | 0.001        | 0.0024       | 0.00073              | 0.00066              |
| 0.00256      | 0.0021       | 0.0029       | 0.00033              | 0.00046              |
| 0.00273      | 0.0022       | 0.0031       | 0.00036              | 0.00053              |
| 0.00306      | 0.0023       | 0.0037       | 0.00063              | 0.00076              |
The above simulation model was used to simulate the moving heat source and the material vaporized after the machining for different values of laser power varying from 11.2 Watt to 18.2 Watt. Same laser power values were used while machining on the machine practically. From the Fig (8) it can be seen that the values of mass of material removed in case of ANSYS and in case of experiment is fairly in agreement with each other. Also after analyzing the graphs and simulation model we found out that:

(1) In all the 3 cases i.e. for materials SS316, Inconel 718 and Ti6Al4V, the ANSYS model shows an increase in MRR with increase in the power values as expected.

(2) For lesser values of power the values of ANSYS shows lesser error as compared to the higher values of laser power in case of SS316.

(3) When the power values are increased above 18.2 Watt, a through hole is machined in the work piece and hence the laser is wasted for a few seconds and therefore an accurate result will not be obtained in the simulation model.
(4) For values lesser than 11.2 Watt, the ANSYS model shows the same amount of material vaporized as in case of 11.2 Watt power because only a single layer of elements is deleted for 11.2 Watt and same number of elements get selected for deletion for lesser power values.

(5) The experimental and simulation values of MRR of Ti6Al4V is significantly lesser than SS316 and Inconel 718 because the value of its thermal conductivity is the least among the three materials. Also the melting point of Ti6Al4V is the highest and hence explains the least value of MRR.

(6) Only for the lower power values of Inconel 718, the values of MRR in ANSYS are lower than the Experimental values. This may be due to some experimental errors.

8. Conclusions
It can be concluded by seeing the graphs that with the increase in power the MRR increases in both the model and the experiments. Also there is a small error in between the MRR values of ANSYS model and the MRR values of the experiments. In case of Ti6Al4V the MRR is comparatively lesser than the other two materials due to its lower value of thermal conductivity. This work illustrates that ANSYS 18.2 can be used for simulation of laser machining processes to get a relation between parameters of the process with the output of the process and also to predict the output of the process without practically carrying out the process. However, detailed simulation for melting of material etc. is challenging to model with this software. Also nonlinear behavior of materials cannot be modeled using this software.

9. References
[1] Jihong Yang, Shoujin Sun, Milan Brandt, Wenyi Yan. (2010, August). "Experimental investigation and 3D finite element prediction of the heat affected zone during laser assisted machining of Ti6Al4V alloy". Journal of Materials Processing Technology 210 (2010) 2215–2222.
[2] J.I. Arrizubieta, F. Klocke, S. Gräfe, K. Arntz, A. Lamikiz.(2015). "Thermal Simulation of Laser-assisted Turning". Procedia Engineering 132 (2015) 639 – 646.
[3] Fredrick Madaraka Mwema. (2017, January 31st). "Transient Thermal Modeling in Laser Welding of Metallic/Nonmetallic Joints Using SolidWorks® Software". International Journal of Nonferrous Metallurgy, 2017, 6, 1-16.
[4] John Romano, Leila Ladani, Magda Sadowski. (2015). "Thermal Modeling of Laser Based Additive Manufacturing Processes within Common Materials". Procedia Manufacturing, Volume 1, 2015, Pages 238–250.
[5] XueFeng Wu, Bowen Zhao, GaoCheng Feng. (2015). "Thermal and cutting process simulation analysis of laser assisted milling of Inconel718". Joint International Mechanical, Electronic and Information Technology Conference (JIMET 2015).
[6] BEGIC, D[erzija]; BIJELONJA, I[zet]; KULENOVIC, M[alik] & CEKIC, A[hmet]. (2011). "Numerical Simulation Of The Laser Beam Drilling Process". Annals of DAAAM for 2011 & Proceedings of the 22nd International DAAAM Symposium, Volume 22, No. 1, ISSN 1726-9679, ISBN 978-3-901509-83-4.
[7] S. A. Tsirkas, P. Papanikos, Th. Kermanidis. (2002, September 11th). "Numerical Simulation of the laser welding process in butt-joint specimens". Journal of Material Processing Technology 134 (2003) 59-69.
[8] Junke Jiao, Xinbing Wang. (2007, May 27th). "A numerical simulation of machining glass by dual CO2 laser beams". Optics and Laser Technology 40 (2008) 297-301.
[9] B. Shi, H. Attia, R. Vargas, S. Tavakoli. (2008, December 11th). "Numerical and Experimental investigation of laser assisted machining of Inconel718". *Machining Science and Technology: An International Journal, 12:4*, 498-513.

[10] R. K. Adhitan, N. Raghavan. (2017, June). "Transient thermo Mechanical modelling of stress evolution and re-melt volume fraction in electron beam additive manufacturing process". *Procedia Manufacturing 11* (2017) 571-583.

[11] R. Glardon, N. Karapatis, V. Romano, *Influence of Nd:YAG parameters on the selective laser sintering of metallic powders*, Annals of the CIRP 50 (2001) 133–136.

[12] Maturose Suchatawat. (2011). "Mathematical Modelling Of Multiple Pulsed Laser Percussion Drilling".

[13] https://www.laserfocusworld.com/articles/print/volume-53/issue-01/features/annual-laser-market-review-forecast-where-have-all-the-lasers-gone.html

[14] http://www.me.iitb.ac.in/~ramesh/courses/ME677/thermal_modeling1.pdf

[15] https://www.researchgate.net/publication/277248363_A_Two_Dimensional_Analytical_Evaluation_of_Temperature_Fields_in_Selective_Laser_Sinteringfigures?lo=1&utm_source=google&utm_medium=organic

[16] https://www.nuclear-power.net/nuclear-engineering/heat-transfer/thermal-conduction/heat-conduction-equation/

[17] https://www.nist.gov/%3Cfront%3E/fire-dynamics?o=37981