

Finite Element Analysis of Laser Drilling on Ti-6Al-4V Alloy



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Abstract Titanium alloy (Ti-6Al-4V) is high strength and high thermal resistance alloy. Hole formation is very difficult on this material by traditional drilling process. Laser drilling is an untraditional method that is used for creating hole on titanium alloy. Laser drilling is a thermal energy-based machining process. Selected input parameters and their value affect material quality characteristics. In present study, temperature and thermal stress distribution have been predicted on selected parameters (power and cutting speed) for through-hole formation of 2 mm diameter on titanium alloy during Nd:YAG laser drilling. Finite element software (ANSYS) has been used to simulate the problem and found predicted selected responses are suitable for laser drilling of titanium alloy.

Keywords ANSYS · Heat flux · Laser drilling · Ti-6Al-4V

1 Introduction

Laser drilling is thermal-based machining process. Thermal energy of laser beam is used to remove material during laser drilling. High precise laser beam is concentrated on material. Thermal energy is absorbed by workpiece, and there is an increase in temperature of contact surface area. Once temperature reaches above melting temperature of workpiece, molten process starts. Molten material is removed by using high pressure assist gas, but it develops hole taper [1–6].

Laser drilling parameters and material properties affect material removal process. Pulse frequency, laser power, assist gas pressure, and cutting speed are some laser

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parameters. Thermophysical properties, material reflectivity, and thickness are material properties. Hole quality may be controlled by controlling of these parameters [4–16].

Titanium grade V (Ti-6Al-4V) is a high strength with high thermal resistance material. Conventional drilling process is not suitable for this kind of (difficult to cut) material. Laser drilling may be used to perform drilling operation on this material [1, 2, 17].

Laser machining process is known for precision machining process. It is very costly process, and high skilled operators are required for performing operation [3, 4].

Some researchers have introduced finite element simulation technique for material removal in laser machining process. In this technique, constant temperature has been used as melting temperature heat source [1–3, 7–9, 15, 16, 18]. Researchers have adopted Gaussian distributed heat source as laser heat source in their study for modeling of drilling process. Finite element method (FEM) is used to create model to analyze thermal stress and temperature distribution on workpiece surface during laser drilling. Various FEM-based software, i.e., ANSYS and COMSOL are used to analyze any type of thermal or structural problem. Following assumptions are used in ANSYS to derive a model [7, 8, 19]:

- a. Material is opaque and isotropic.
- b. Gaussian distributed heat source is used for spatial distribution at TEM₀₀ mode.
- c. Density of laser energy is equal along workpiece thickness with an appropriate focus depth.
- d. No vaporization occurs during immediately removal of molten material by pressure of assist gas.
- e. Material is re-solidified in small fraction. Thus, phase change is neglected.
- f. Inert gas cooling effect is negligible.

2 Material and Methodology

Laser beam machining is a thermal-based machining process and it is very costly machining process [5, 6, 12–14]. So, theoretical analysis has been performed by using FEM-based ANSYS software before experimental study. Once selected input parameters are validated theoretically, then these parameters may be adopted for experimental study.

In this paper, ANSYS software has been used as simulation technique to analyze temperature and thermal stress distribution during Nd:YAG laser drilling to see the effect of decided laser input parameters to create through-hole. Ti-6Al-4V material sheet of 1.2 mm thickness has been used as workpiece to create through-hole of 2 mm diameter.

2.1 Heat Transfer Analysis

Heat source modeling is used to analyze thermal behavior of laser beam during laser drilling. Gaussian beam shape is used as laser beam for thermal modeling. Because of high power, Gaussian beam may be focused on a smallest diameter [9]. Beer–Lambert law is used derive governing equation for transmitted laser energy to workpiece of z thickness. Laser energy is given by [8]:

$$S(z) = Ie^{-\delta z} \tag{1}$$

where

- P = Laser output power in watts
- I = Intensity of laser, i.e., $P/\pi r^2$ (W/m²)
- δ = Coefficient of absorption (m⁻¹)

Where absorption coefficient of metal has taken around $5e7$ m⁻¹. So, absorption of laser energy takes place in a very shallow region with a depth of only a fraction of wavelength of incident radiation. Adequate surface heat flux (W m⁻²) can be calculated by follows expression [7, 8, 19]:

$$S = Ie^{-\delta} (1 - s)e^{-(x-r \sin \omega t)^2 + (y-r \cos \omega t)^2/a^2} \tag{2}$$

where

- a = Gaussian parameter
- s = Surface reflectivity
- δ = absorption coefficient
- ρ = Material density (Kg/m³)
- $r = \sqrt{x^2 + y^2}$ where x and y are coordinate axes (laser drilling radius)
- ω = Cutting speed in rpm

Transverse electromagnetic mode (TEM) is used to characterize profile of laser beam. These modes are denoted in form of TEM_{op}, where ‘o’ and ‘p’ are in subscript, indicate number of nodes in orthogonal direction to propagation of beam. Normally TEM₀₀ or TEM₀₁ modes are used to characterize laser beam profile. TEM₀₀ has Gaussian spatial distribution. It also has uniform phase front. There is smooth drop off radiance from center of beam. So, TEM₀₀ is best mode for LBM. It also reduces effect of diffraction and creates small spot size [4].

Heat transfer model must be three-dimensional and transient in laser machining. Transient thermal model can be written as [4,510]:

$$\rho c(T) \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(k(T) \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k(T) \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(k(T) \frac{\partial T}{\partial z} \right) + Q \tag{3}$$

where $c(T)$ and $k(T)$ are function of temperature of specific heat and thermal conductivity, respectively. Q is internal heat generation rate.

2.2 Thermal Stress Analysis

As laser beam moves, molten material re-solidified rapidly in heated zone, because cooling rate increases in heated zone. High cooling rate develop thermal stress in workpiece [8, 19].

Thermal stress is calculated by given Formula as [8]:

$$\sigma_{\text{therm}} = \frac{E\alpha\Delta T}{1 - \mu} \tag{4}$$

where

E = Modulus of elasticity

α = Coefficient of thermal expansion

μ = Poisson’s ratio

ΔT = Temperature difference

Equivalent von Mises stress is found out by given Formula as [8]:

$$\sigma_m = \sqrt{\frac{(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2}{2}} \tag{5}$$

where

σ_x = Principal stress from any point in x -direction of principal axis

σ_y = Principal stress from any point in y -direction of principal axis

σ_z = Principal stress from any point in z -direction of principal axis

These principal stresses are calculated and putting in Eq. 5 to find out σ_m . If von Mises stress reaches at yield strength of material then plastic deformation occurs. Thermal-related material properties are taken from Table 1 to calculate thermal stress.

Table 1 Thermophysical properties of titanium alloy (Ti-6Al-4V) [7]

Melting range 1873 K-1933 K; Modulus of Elasticity–113.6 GPa;
Poisson’s ratio–0.34; Density–4430 kg/m³

Temperature (K)	Thermal conductivity (W/m K)	Specific heat (J/Kg K)
373	30.5	300
473	24.5	465
673	20.4	551
873	19.4	591
1073	19.7	633
1273	20.7	675
1473	22	620
1773	24.5	686

The temperature-dependent properties of Ti-GradeV used in calculation are shown in Table 1. The workpiece is clamped from surrounding. No external loading is assumed on workpiece.

2.3 Finite Element Simulation (FES)

FES has used same process parameters adopted in experiments. Therefore, FEM-based software ANSYS is used to find out distribution of temperature and thermal stress in workpiece [7, 8, 19].

There are total three stages in ANSYS to solve any kind of problems. These are preprocessing, solution, and post-processing. Each stage has number of steps. These three stages have following steps for solving the problem in ANSYS [8, 18, 19]:

Stage 1 Preprocessing

1. Specify Jobname.
2. Define element type. (SOLID187 is 3D element for transient thermal and structural analysis).
3. Define material properties. (thermal conductivity, coefficient of expansion, specific heat, modulus of elasticity, etc.)
4. Create 3D model.
5. Specify meshing size to control density.
6. Meshing (tetrahedral) to build elements and nodes.

Stage 2 Solution

7. Specify process parameters as heat flux and define position on material sheet.
8. Solve.

Stage 3 Post-processing

9. Plot temperature distribution and thermal stress distribution.
10. Nodes selection along center of plate.
11. Listed centered nodes location.
12. Listed temperatures and stresses at each node.

Re-analysis

13. Modify mesh/re-analyze.

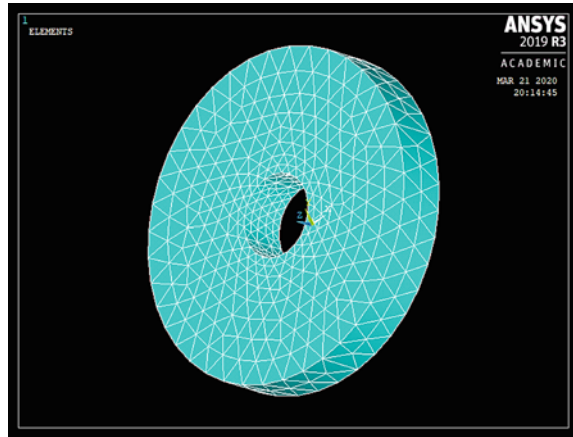
Exit

14. Exit and saved all data.

2.4 Model for Transient Analysis Using ANSYS

Firstly, transient thermal model is prepared to find out temperature distribution in material. These results are used as input data for transient structural analysis. ANSYS

Fig. 1 Meshing of object in ANSYS



Parameter Design Language (APDL) is used as programming language to prepared model for transient analysis. SOLID187 has been used as thermal element type for transient thermal analysis. But, SOLID187 has been implemented as structural element type for transient structural analysis and temperature from thermal stress analysis is used as input data. Size of element meshing plays an important role in finite element analysis, because coarse meshing can give large errors in result. Same mesh size has been used for both type of analysis with different element types. Fine meshing gives best result, but this type of meshing increases computational time. Appropriate element size is chosen based on mesh convergence parametric studies [12–15, 18]. For current study, 0.01 mm element size and tetrahedral meshing have been chosen for 1.2 mm thick Ti-6Al-4V alloy sheet. Selected element size and type of meshing are appropriate for computational efficiency and simulation accuracy to create a hole of 2 mm diameter. Therefore, a circular disk of radius 1 mm with 1.2 mm thickness has been taken, and mesh comprises about 40,000 for same thickness. The details about the mesh are presented in Fig. 1.

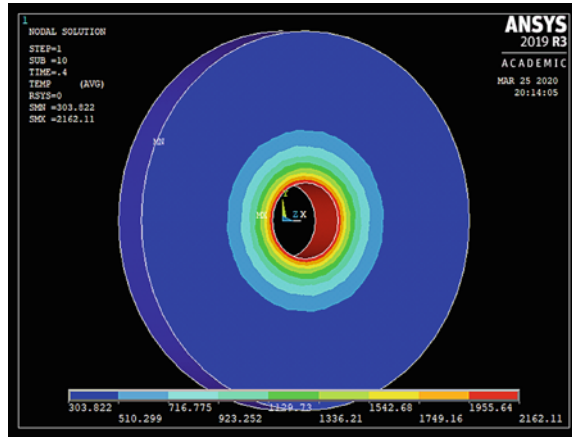
3 Results and Discussion

3.1 Transient Temperature Distribution Analysis

Thermal distribution can be studied with real time by this analysis. Thermal properties like thermal conductivity, expansion coefficient, and specific heat have been taken from Table 1.

Heat flux has been used for thermal input parameter in ANSYS mechanical APDL 2019R3. That has been calculated from Eq. 2, where laser power and cutting speed have been taken 150 W and 60 mm/min that has been taken from decided experimental

Fig. 2 Temperature distribution for Ti-grade V alloy



input parameters. Initial (ambient) temperature has been taken 303 K. Heat flux is calculated $22e^6 \text{ W/m}^2$ and time taken to complete the process in 0.4 s. Temperature distribution for hole diameter 2 mm has been shown in Fig. 2 for Ti-alloy of 1.2 mm thick sheet during thermal analysis. Maximum temperature is 2162.11 K that has been found around hole surface as shown in Fig. 2. Melting temperature for this material is 1933 K from Table 1, maximum temperature is approximately 229 K more than melting temperature. This temperature is enough to evaporate molten metal from workpiece. So, transient thermal analysis model is valid for proven that calculated temperature is enough to perform hole formation for 1.2 mm thick sheet.

3.2 Transient Thermal Structural Analysis

This type of analysis is generally used for study of stress on any type of surface. In laser machining process, thermal energy is used to perform any type of machining operation. By this analysis, thermal stress may be calculated. Temperature has been taken as input parameter here only, i.e., around hole surface. Input temperature 2162.11 K is taken to find out resultant thermal stress (von Mises stress). Mechanical properties like elastic constant and thermal coefficient have been taken from Table 1 to find out thermal stress.

Actual hole diameter at entrance is quite more than desired hole diameter during laser drilling operation due to convergent–divergent characteristics of laser beam [13–16, 18]. It can be seen clearly from Fig. 3, where maximum displacement is 0.013 mm in hole diameter 2 mm. Thermal stress (von Mises stress) distribution is showing in Fig. 4. Maximum von Mises stress has been found out 3130 MPa around hole circumference that is much greater than ultimate stress of titanium grade V (950 MPa) from Table 1.

Fig. 3 Displacement diagram

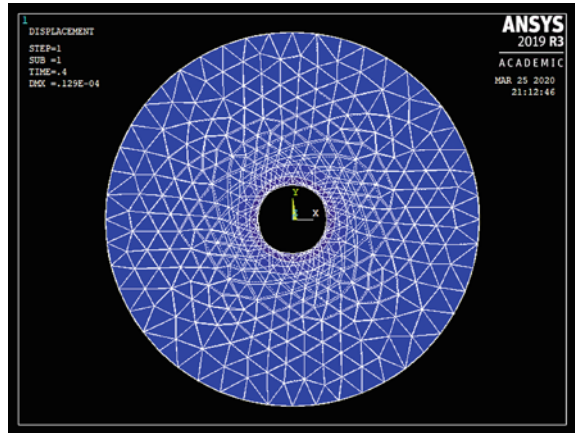
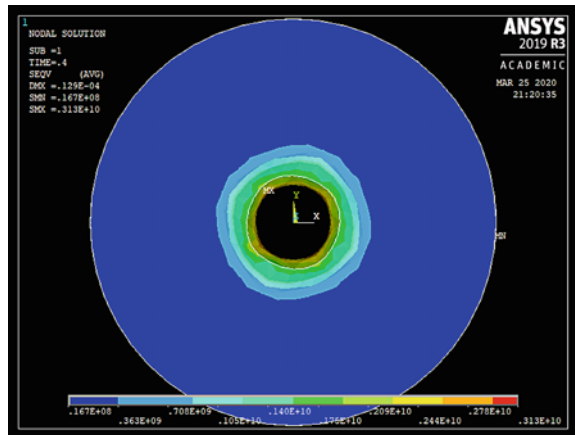


Fig. 4 von Mises stress (thermal stress) analysis



It has been proven that all decided input parameters for thermal distributions are correct and validated by this FEM analysis. Now these selected parameters (power and cutting speed) may be used for further experimental work.

4 Conclusions

It has been proven that selected power and cutting speed is suitable for performing a hole for Nd:YAG laser drilling for 2 mm hole diameter. After applying FEM-based simulation technique (ANSYS), following points have been observed:

Maximum temperature found 2162.11 K around hole circumference that temperature is sufficient to melt the material because this value is much higher from melting

temperature (1933 K) of Ti-6Al-4V alloy. Maximum thermal stress found 3130 MPa around hole circumference is much more than ultimate stress (950 MPa) of Ti-6Al-4V alloy. Maximum displacement has been found during hole formation 0.013 mm for 2 mm hole diameter.

References

1. Steen WM(1991) In: Laser material processing, Springer, London, pp 72–80
2. Yilbas BS, Arif AFM, Abdul Aleem BJ (2010) Laser cutting of rectangular blanks in thick sheet metal: effect of cutting speed on thermal stresses. *J Mater Eng Performance* 19:177–184
3. Kim MJ (2005) 3D finite element analysis of evaporative laser cutting. *Appl Math Model* 29:938–954
4. Chryssolouris G (1991) In: Laser machining-theory and practice, Mechanical Engineering Series Springer
5. Reda R, Magdy M, Rady M (2019) Ti–6Al–4V TIG weld analysis using FEM simulation and experimental characterization. *Iran J Sci Technol Trans Mech Eng* 44:765–782
6. Sifullah AM, Nukman Y, Hassan MA, Hossain A (2016) finite element analysis of fusion laser cutting on stainless steel-304. *ARPJ J Eng Appl Sci* 11(1):181–189
7. Arif AFM, Yilbas BS (2008) Thermal stress developed during laser cutting process: consideration of different materials. *Int J Adv Manuf Technol* 37:698–704
8. Nyon KY, Nyeoh CY, Mokhtar M, Abdul-Rahman R (2012) Finite element analysis of laser inert gas cutting on inconel 718. *Int J Adv Manuf Technol* 60:995–1007
9. Bahotre NB, Harimkar SP (2008) In: Laser fabrication and machining of materials, 186–187. Springer, New York, pp 51–52
10. Ion JC (2005) In: Laser processing of engineering materials, Elsevier, Oxford, pp 168–169
11. Radovanovic M (2006) Some possibilities for determining cutting data when using laser cutting. *J Mech Eng* 52:645–652
12. Namdev S, Pandey A, Pandey AK (2019) Optimization of hole taper in machining of SS316L alloy sheet using laser beam drilling. *Int J Adv Sci Technol* 28(18):771–778
13. Namdev S, Pandey A, Pandey AK, Kumar R (2019) Experimental analysis on titanium grade-V sheet using laser beam machining process. *Int J Adv Sci Technol* 28(20):678–690
14. Liverani E, Toschi S, Ceschini L, Fortunato A (2017) Effect of selective laser melting (SLM) process parameters on microstructure and mechanical properties of 316L austenitic stainless steel. *J Mater Process Technol* 249:255–263
15. Liu Y, Zhang J, Pang Z (2018) Numerical and experimental investigation into the subsequent thermal cycling during selective laser melting of multi-layer 316L stainless steel. *Opt Laser Technol* 98:23–32
16. Suryawanshi J, Prashanth KG, Ramamurty U (2017) Mechanical behavior of selective laser melted 316L stainless steel. *Mater Sci Eng* 696:113–121
17. Arif AFM, Yilbas BS (2008) Thermal stress developed during the laser cutting process: consideration of different materials. *Int J Adv Manuf Technol* 37:698–704
18. <https://www.ansys.com/products/structures/thermal-analysis>
19. Yilbas BS, Akhtar SS, Keles O (2013) Laser hole cutting in aluminum foam: Influence of hole diameter on thermal stress. *Opt Laser Eng* 51:23–29