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Thermal Analysis of Laser Trepan Drilling of Zirconia Toughened Alumina Plate

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Abstract

Attributes of Zirconia Toughened Alumina (ZTA) ceramic like toughness and wear resistance make it robust material over other ceramics. It is mainly used to make parts for medical, cutting tools and aerospace industries. Laser trepan drilling (LTD) is found suitable advanced machining process for circular cutting in difficult-to-cut materials. But being a thermal energy-based process, thermal analysis is essential in order to get uniform hole shape and size with temperature and stress field history. The present research paper investigates numerical study for LTD of 6.0 mm thick ZTA plate. The effect of pulse width, pulse frequency, and trepanning speed on temperature and von Mises stress has been studied.

Keywords

Zirconia toughened alumina, Laser trepan drilling, Hole depth, Temperature, Stress

Introduction

The ZTA ceramic is attributed with admirable toughness, wear resistance, and strength [1-3]. These properties make ZTA suitable for a wide range of applications. ZTA is used to manufacture armor, cutting tool inserts, pump, impeller, and orthopedic joints [3-4]. Laser machining has competence to machine difficult to machine structural ceramics [5-6]. In laser machining process high intensity laser energy falls on required work surface and produces high temperature and stresses that cause undesired attributes near machined zone. To overcome these problems researchers have developed theoretical and numerical models to predict the range of processing parameters that suit the machining of different ceramics. To generate holes above 1 mm diameter, LTD is found to be the best method [4, 7-9]. Yilbas et al. [10] studied laser cutting on 3 mm thick alumina ceramic. Temperature and stress were analyzed theoretically by using ABAQUS software. Literature review revealed that most theoretical and experimental investigations have been carried out on laser drilling of alumina ceramics. This paper presents numerical analysis of LTD in 6.0 mm thick ZTA. The effect of pulse width, pulse frequency, and trepanning speed on formation temperature distribution and von Mises stress have been investigated.

Materials and Methods

Finite element analysis for LTD process of thick ZTA plate is done. Simulation is carried out by using the ANSYS® Workbench software. To analyze the temperature and stress during the LTD process of 6.0 mm thick ZTA plate, a geometric model has been developed as shown by figure 1. To simulate the real LTD process in finite element analysis is difficult. Therefore, the numerical simulation has been done based on the following assumptions.

a. Work material is considered homogeneous and isotropic in nature.

b. Work material properties do not change with temperature.

c. Laser heat flux on work material is opined as Gaussian type distribution.

d. The convection and radiation losses from the work surface i.e., B_3, B_4, B_5, B_6, and B_7 are neglected. Affected work regime from laser heat flux exceeds the melting temperature; it is considered that molten material gets ejected.

To determine the maximum temperature within work domain KLMNOPQ as shown by figure 1, three-dimensional heat conduction equation and boundary conditions have been used which are represented by equations (1-7) [11-12].

$$k\left[\frac{\partial}{\partial x}\left(\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\frac{\partial T}{\partial z}\right)\right]+q=\rho C_p\frac{\partial T}{\partial t} \quad (1)$$

$$q = I_0 \text{ x } e^{\frac{\ddot{u}^2}{R^2}} \quad (2)$$

$$I_0 = \frac{2 \text{ x energy density}}{\text{time x plate thickness}} \quad (3)$$

$$T = T_0\left(293.15\ °K\right) \text{ at } t = 0 \quad (4)$$

$$k\frac{\partial T}{\partial n} = q \quad \text{on} \quad B_1 \quad (5)$$

$$k\frac{\partial T}{\partial n} = -h\left(T - T_0\right) \quad \text{on} \quad B_2 \quad (6)$$

$$\frac{\partial T}{\partial n} = 0 \quad \text{on} \quad B_3, B_4, B_5, B_6 \text{ and } B_7 \quad (7)$$

$$\acute{o}_{th} = \frac{E}{1-\nu} \quad (8)$$

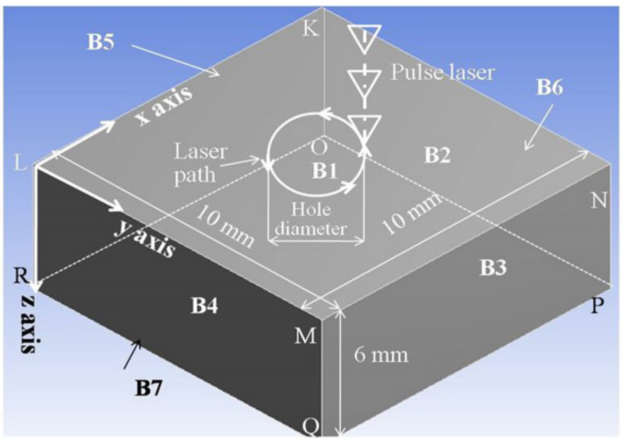

Figure 1: Schematic view of geometric model for laser trepan drilling into work material.

Where, T = transient temperature (°K), C_p = specific heat (J/kg °K), ρ = material density (kg/m^3), k = thermal conductivity (W/m °K), q = laser heat flux (W/m^3), R = beam spot radius (mm), v = trepanning speed (mm/sec), r (mm) = radial distance from laser beam axis, I_o = laser power intensity (W/mm^3), n = outward normal to the boundary surface, h = natural convective heat transfer coefficient (Wm^{2}k^{-1}), σ_{th} = thermal stress, α = coefficient of thermal expansion, and ΔT = temperature difference.

Equation (4) represents the pre-LTD condition. While equation (5) and equation (6) represent the region of laser heat flux on boundary B_1 and natural convective heat transfer on boundary B_2, respectively. Equation (7) represents the no heat transfer across boundaries i.e., B_3, B_4, B_5, B_6, and B_7. The temperature difference during laser trepanning of ZTA due to heating and cooling formed thermal stress which is represented by equation (8). A three-dimensional fine mesh model is shown in figure 2.

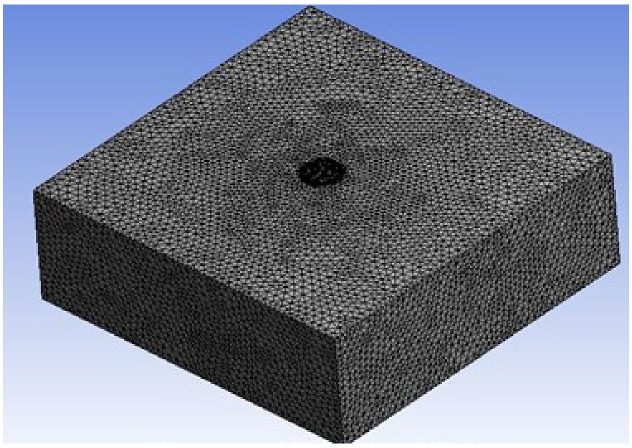

Figure 2: Three-dimensional meshed geometry.

Results

In simulation laser heat flux moves along the periphery of the hole and it flows from top to bottom side. Once laser heat flux exceeds the melting temperature; it is considered that molten material gets ejected. The maximum values of temperature and von Mises stress generated during numerical simulations for LTD process of 6.0 mm thick ZTA match up to distinct input parameters are shown in table 1. The formation of hole depth and von Mises stress at different values of input parameters during simulation are shown by figure 3 and figure 4, respectively.

Discussion

The consequence of trepanning speed, pulse width, and pulse frequency on temperature (at top and bottom surface of drilled hole) and von Mises stress (at top circumference of drilled hole) are shown by figure 5, respectively. In figure 5a and 5b, the trend of temperature and von Mises stress profile are almost same while in figure 5c it is found vice versa. When pulse width and pulse frequency raise temperature and von

Table 1: Predicted values of maximum temperature and stress.

Process Parameters	Values	Hole Temperature (˚K)		von Mises Stress (GPa)
		Top	Bottom	
Pulse Width (ms)	4	2484.9	1525.6	2.01
	6	3162.2	1980	4.013
	8	3955	2681.4	6.6
	10	4595.7	2824.2	5.82
	12	5312.5	3240.6	6.98
Pulse Frequency (Hz)	8	3064.7	1728	3.01
	10	3879	2399.9	5.01
	12	3955	2681.4	6.6
	14	4552.5	2795	6.72
	16	5174.9	3479.5	6.85
Trepanning Speed (mm/sec)	0.083	6746	4091.2	8.95
	0.167	6029.2	3657.4	7.97
	0.333	3955	2681.4	6.6
	0.500	3064.7	1728	3.01
	0.667	2484.9	1525.6	2.01

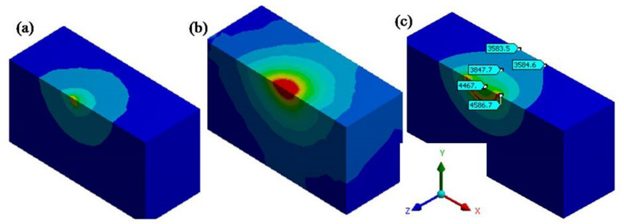

Figure 3: Simulation images of trepan drilled hole at different process parameters.

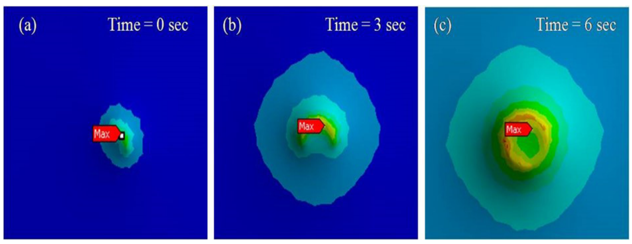

Figure 4: Simulation images of von Mises stress during simulation of LTD process.

Mises stress on hole circumference increases. Because energy density is high at higher pulse width and pulse frequency. When trepanning speed increases, energy density decreases hence temperature and von Mises stress decreases. The fact is, at lower trepanning speed dealings time between laser and work piece is more due to which more energy is available. Developed maximum temperature and von Mises stress caused poor hole quality. The minimum and maximum temperature values at top and bottom of hole surface are found 2484.9 ˚K and 6746 ˚K and 1525.6 ˚K and 4091.2 ˚K, respectively. While, least and highest von Mises stress found as 2.01 GPa and 8.95 GPa, respectively along circumference of drilled hole at pulse

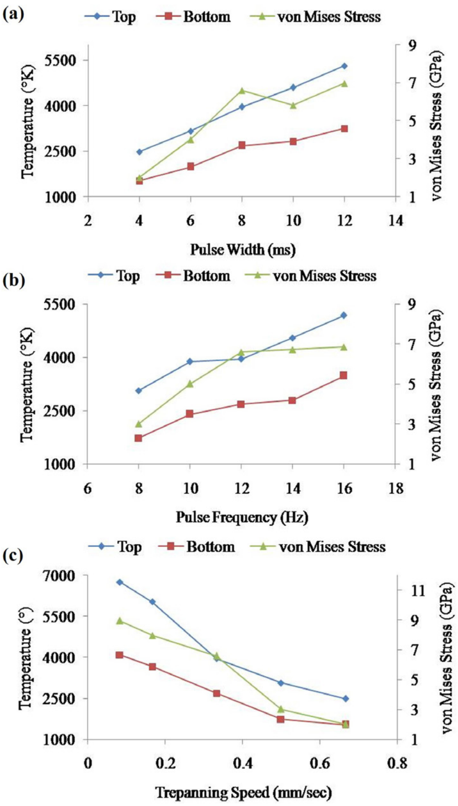

Figure 5: Graphs of temperature (at top and bottom side) and von Mises stress (at top circumference of drilled hole) during LTD process corresponding to **(a)** pulse width, **(b)** pulse frequency, and **(c)** trepanning speed.

width (4 ms) or trepanning speed (0.667 mm/sec) and trepanning speed (0.083 mm/sec), respectively.

To validate the simulated hole depth, experiments have also been conducted as shown microscopic images in figure 6. Figure 6a shows that complete molten material is not ejected at lower pulse width (4 ms) because laser energy density is not sufficient to melt complete thickness of ZTA. Similarly, figure 6b shows irregular circularity of hole at values of pulse width (8 ms), pulse frequency (12 Hz), and trepanning speed (0.333 mm/sec). Figure 6c shows failure of hole at lower value of trepanning speed where energy density is higher. The trend between simulated and actual depth of drilled hole found almost similar.

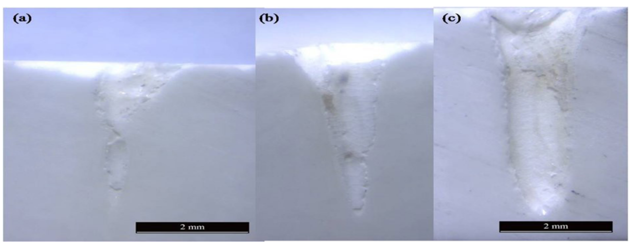

Figure 6: Microscopy images of sectioned drilled hole.

Conclusions

In the present study finite element thermal analysis of LTD into ZTA has been done. The main findings are given below:

- A finite element based numerical model developed. The developed model is used to investigate the temperature distribution and von Mises stress in ZTA plate during LTD.
- Laser energy density at lower values of pulse frequency, pulse width, and trepanning speed was not sufficient to cut through hole in ZTA plate.
- Numerically predicted values of minimum temperature at top and bottom of hole surface, and von Mises stress along circumference of drilled hole are found 2485 °K and 1526 °K; and 2.01 GPa, respectively, at trepanning speed 0.667 mm/sec.
- Maximum values of temperature at top and bottom of hole surface, and von Mises stress along circumference of drilled hole are found 6746 °K and 4091 °K, and 8.95 GPa, respectively, at trepanning speed 0.083 mm/sec.
- Simulated and experimental drilled hole depths are verified that show energy density 16.5 J/m^2 is threshold value for through cut hole.

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Conflict of Interest

No known conflict of interest in this manuscript.

Credit Author Statement

Surendra K. Saini: Study design, Writing - original draft preparation; Avanish K. Dubey: Writing - review and editing; Ajay K. Maurya: Data analysis. All the authors read and approved the manuscript.

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