Micromachining of metals and thermal barrier coatings using a 532 nm nanosecond fiber laser

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Abstract

In this study, a 532 nm nanosecond pulsed Ytterbium fiber laser is used to study the physical interactions between pulsed laser beam and metal or ceramic materials. Thermal ablation model was used to determine the ablated material volume and dimensions subjected to stationary pulses and a moving laser beam. Results are compared between modelling and experimental data. Optimized machining parameters are recommended with the aim of maximum process efficiency and minimum thermal effects such as recast layer, edge protrusions and microcracks.

1. Introduction

Precision manufacturing of the shaped film cooling holes on turbine blades is a challenge especially when the metal blades are coated with thermal barrier coatings (TBC). Compared with the traditional high energy millisecond pulsed laser drilling or micro-scale electric discharged machining (EDM) processes, high frequency short-pulsed laser combined with high speed galvo scanner has demonstrated unique advantages in micromachining directly on ceramics or metals with high quality [1]. Hybrid process with short-pulsed laser drilling through TBC coating followed by the micro-EDM drilling through the base metal is an efficient way to drill shaped cooling holes with high quality [2].

Laser drilling has been developed for decade and has the advantages to machine on hard materials such as superalloys and ceramics with no tool wear, high accuracy and fast process rate. Early studies of laser drilling focused on using Nd:YAG lasers which produce millisecond pulses and high pulse energy up to 15 J [3-6]. Due to the long pulse duration, cracking and delamination can be barely avoided. Ultra short
(picosecond to femtosecond) pulsed laser process has been demonstrated to solve these problems. With a Ti:sapphire laser (wavelength 780 nm and pulse duration 150 fs), Feng et al. [7] reported that conventional defects such as spatter, recast layer and micro-crack were completely absent. Their conclusion was also supported by Das and Pollock [8] who examined the shape and surface finish of the hole wall. According to their study, femtosecond machining produced no micro-crack and recast defects. However, they also found limitation that femtosecond pulse laser still led to minor ablative material loss from the surface of the YSZ coating around the holes. Although the femtosecond technique seems to produce high quality holes, its industrial application is still limited due to its very high cost and slow process rate [8]. A femtosecond laser costs as much as 10 times high compared to the cost of a fiber nanosecond lasers. By applying nanosecond pulsed laser, the material defect problem, processing time problem and overall cost may be compromised.

In this study, a nanosecond pulsed Ytterbium fiber laser is used to study the physical interactions between pulsed laser beam and metal or ceramic materials. Thermal ablation model was established to determine the ablated material volume and dimensions subjected to stationary pulses and a moving laser beam. Results are compared between modelling and experimental data. Optimized machining parameters are recommended with the aim of maximum process efficiency with minimum thermal effects such as recast layer, edge protrusions and microcracks.

2. Modeling and Experimental Method

2.1. Heat transfer model

In this study, a transient heating process on a thin layer of material irradiated by a pulsed laser beam is modeled through finite element method (FEM). During heating, the material is partially melted and vaporized, leaving a laser ablated crater geometry after 1 nanosecond pulse. A 2D rectangular geometry with the dimension of 120 x 5 μm was used in the model representing the workpiece as shown in fig. 1. The top surface of the workpiece is subjected to the laser irradiation with a beam waist of $2w$ and heat lost due to convection and radiation. The boundary conditions at the other surfaces of the workpiece are assumed as adiabatic interface. The heat transfer governing equation is given as

$$\rho c_p \frac{\partial T}{\partial t} + \rho c_p u_{\text{trans}} \cdot \nabla T = \nabla \cdot \left( k \nabla T \right) + Q$$  \hspace{1cm} (1)

Where, $\rho$ is the density (kg/m$^3$), $c_p$ is the specific heat capacity at constant pressure (J/(kg·K)), $k$ is the thermal conductivity (W/(m*K)), $T$ is absolute temperature (K), $Q$ contains heat sources (W/m$^3$). To account for the latent heat of melting and vaporization, $c_p$ is defined as a segment function of temperature as shown in fig. 2, where the latent heat was uniformly distributed over 100 K step around the melting or vaporization temperature.
The boundary condition on the top surface can be expressed as where

\[- \mathbf{n} \cdot (-k \nabla T) = q + h \cdot (T_\infty - T) + \varepsilon \sigma (T_{\text{sur}}^4 - T^4), \tag{2}\]

\[q = \frac{2(1 - R) P_c}{\pi w^2} \exp \left(-2 \frac{x^2}{w^2}\right) \tag{3}\]

is the absorbed laser power density in Gaussian distribution, $h$ is surface heat transfer coefficient, $T_\infty$ and $T_{\text{sur}}$ are the ambient temperature, $\varepsilon$ is the material emissivity, $\sigma$ is Stefan-Boltzmann constant, $R$ is the reflectivity of material, $P_c$ is the laser peak power. COMSOL Multiphysics® software package was used as the FEM modeling tool to solve for this heat transfer model.

Moving mesh method is used in the FEM model to simulate the recession of material surface due to the laser ablation. The mesh at the top boundary of the calculating domain is movable according to the velocity and direction determined by the melting and vaporization phenomena during laser drilling. A drilling model based on ablation mass equilibrium developed by Semak and Matsunawa [9] is used to calculate the drilling velocity,

\[v_d = \frac{1}{2} \left[ \frac{\rho_m}{\rho_s} \cdot v_v + \sqrt{\left( \frac{\rho_m}{\rho_s} \cdot v_v \right)^2 + 4 \cdot \frac{a_m}{r_1} \cdot \frac{\rho_m}{\rho_s} \cdot v_m} \right] \tag{4}\]
where \( r_l \) is the beam radius, \( a_m \) is the thermal diffusivity of melts, \( \rho_s \) and \( \rho_l \) are the densities of solid and liquid phases respectively, \( v_m \) is the melt ejection velocity, \( v_v \) is the vaporization velocity. The evaporation front velocity \( v_v \) is determined by the melt’s surface temperature \( T_s \)

\[
v_v = C_0 \exp \left( -\frac{U}{T_s} \right) \quad \text{and} \quad U = \frac{M_a L_v}{N_a k_b}
\]

where \( C_0 \) is the speed of sound in the condensed phase, \( M_a \) is the atomic mass, \( L_v \) is the latent heat of evaporation, \( N_a \) is Avogadro’s number, \( k_b \) is Boltzmann’s constant. Considering the recoil pressure effect of vaporization, \( v_m \) can be determined through the following Bernoulli’s equation and saturated vapor pressure equation

\[
P_r = \frac{\rho_m \cdot v_m^2}{2} = A \cdot B_0 \cdot T_s^{-1/2} \cdot \exp \left( -\frac{U}{T_s} \right)
\]

where \( A \) is a numerical constant and equal to 0.55, \( B_0 \) is vaporization constant, \( T_s \) is surface temperature.

2.2. Experimental method

A nanosecond-pulsed Ytterbium fiber laser at a wavelength of 532 nm was used in this study. The laser provides a maximum average power of 10 W with 1 ns pulse width and repetition rate up to 600kHz. The near-Gaussian distribution laser beam is delivered through a 2D galvo scanner and is focused by a 170 mm objective lens.

![Cross section micrograph of a laser machined trench on IN718 plate](image)

Grooves were machined with different laser parameters on stainless steel 304 (SS304), copper, Inconel 718 (IN718), and TBC (Yttrium oxide stabilized zirconia) coated IN718 plates. Laser pulse energy, scanning speed, and focus position relative to the workpiece surface, were varied in the experiments to examine their effects on machined trench geometry and quality. The combination of these parameters should give appropriate energy fluence and pulse overlap ratio to produce trenches with maximum material removal rate. Grooves were sectioned transversely to expose their cross-sections. The depth, width and cross-section area of each groove were measured from the microscopic pictures, as shown in fig. 3. At least three sections were examined and measured for each groove.

A semi-empirical model based on the work of Raciukaitis et al. [10,11] is used to interpret the experimental data and derive the optimized material removal rate. The machined groove geometry data
was obtained as functions of the laser spot size, pulse energy and fluence. The volume of crater produced with a single pulse can be determined based on the following empirical equation,

\[ V = \frac{\pi w^2 d_0}{4} \left( \ln \frac{2E_p}{\pi w^2 F_c} \right)^2 \]  

(7)

where \( d_0 \) is a scaling parameter presenting an effective absorption depth; \( w \) is the beam waist of the laser beam; \( F_c \) is the critical threshold fluence, \( E_p \) is the laser pulse energy. When the beam waist reaches a specific value \( w_{\text{max}} \), the ablated volume of a single pulse becomes maximal.

Consider multiple consecutive laser pulse machining, when the beam pulse moves on a workpiece in the positive \( x \) direction, the distance between the centers of two consecutive pulses can be denoted as \( \Delta x \). The overlap of laser pulses accumulates fluence on the same location and affects the shape of machined trench. Assume the displacement between shots is much less than the spot radius, the trench centerline depth \( (y = 0) \) can be calculated as

\[ D(0) = \frac{4wd_0}{3\Delta x} \left( \ln \frac{F_0}{F_c} \right)^2 \]  

(8)

where \( F_0 \) is the laser peak fluence, and \( F_0 = 2E_p/\pi w^2 \). The removal rate of evaporating material at certain pulse repetition \( f \) is

\[ \frac{dV}{dt} = fA \Delta x = f \frac{d_0 \pi}{6} \ln \frac{F_0}{F_c} \left( \frac{3w^2}{2} \ln \frac{F_0}{F_c} - \Delta x^2 \right) \]  

(9)

The evaporation rate is also influenced by a lot of other material properties, such as absorption depth and ablation threshold. However, the laser parameters, such as pulse energy and repetition rate mainly determine the efficiency of laser ablation.

3. Results and Discussion

Relations of the laser fluence and geometric features of the machined trench were also investigated from the experiments. Different laser fluence levels were obtained by varying the laser pulse energy and defocus distance. Fig. 4 shows the trench depth data dependent on the fluence. The best fit logarithmic function curve was plotted according to the relation expressed in eqn. (8). The characteristic parameters were obtained as \( d_0 = 2.03 \mu m \) and \( F_c = 0.2065 \text{ J/cm}^2 \) for SS304, and \( d_0 = 0.372 \mu m \) and \( F_c = 0.022 \text{ J/cm}^2 \) for IN718. The \( d_0 \) and \( F_c \) values are then used in calculating the volume removal rate with eqn. (9).
Fig. 4. Trench depth as function of laser fluence for machining on (a) SS304 and (b) IN718 by twice laser scanning at 4mm/s

Fig. 5 shows the relation of volume removal rate and beam waist compared between experimental data, empirical equation (9) and the results from FEM model. It can be observed that the volume removal rate reaches a maximum value when varying the beam waist. This trend can be observed for both copper and SS304. The experimental data of the trench volume removal rate follows the empirical relation of equation (9) well. The FEM model predicted volume removal rates also follow the same trend. The maximum volume removal rate occurs at almost the same range of beam waist of the experimental and empirical relations for both materials respectively. However, the modelling results predict smaller material removal rates, which could be caused by the ignorance of plasma generation and heat accumulation effect during the real drilling process. At a fixed speed, small beam waist produces high energy density which results in narrow and deep trenches but the volume of material removal is limited. On the other side, a large beam waist always associates with low fluence and leads to low material removal rate when the laser fluence is less than the ablation threshold.

Fig. 6 shows the relations of volume removal rate and laser power compared between SS304, copper, IN718 and TBC materials. It can be observed that, among the four materials, copper and SS304 have the lowest volume removal rates while TBC is the easiest to machine. The volume removal rate generally increases with the increasing of laser power, which has more profound proportional effects on TBC and IN718 compared to SS304 and copper. However, this trend reaches a peak at 7 W and 9 W for TBC and IN718 respectively.

The dependence of the material removal rate from a bulk volume removal experiment is slightly different from the single trench machining results, especially in the small defocus regime. In single trench machining, small defocus always results in the formation of large protrusion and recast layer because of high laser fluence and significant melting and ejection in the deep and narrow trench. In addition, the maximum depth of the single trench machining has the limitation due to the tapered wall which leads to low laser beam absorption. For bulk volume removal, raster scanning with overlapping between adjacent trenches is needed to achieve high bulk ablation rate and low surface roughness.
Machining experiments were performed to study the raster scanning parameters when a bulk material of rectangular volume (1 x 2 mm$^2$) is removed. With the fixed scanning velocity and repeat number, the depth and surface roughness of the rectangular volume were measured. Fig. 7 shows that the raster line spacing (offset) affects the bulk volume removal rate as well as the surface roughness. The line spacing for the best removal rate of IN718 is 20 μm and the overall volume removal rate doesn’t change significantly with the line spacing. However, the volume removal rate increases dramatically with the raster line spacing for TBC.

Although the increase of line spacing may lead to an increase in bulk volume removal rate, the surface roughness also increases correspondingly. Fig. 7b shows the linear profile roughness of machined TBC is greater than IN718. Fig. 8 shows the surface morphology of laser machined IN718 by one-direction raster scanning measured by a 3D microscope, the 1 x 2 mm$^2$ area roughness $R_s$ is measured as 5.96 μm. Fig. 9 shows a 45° film cooling hole machined on TBC coating by using the optimized machining parameters with the 1 nanosecond pulsed fiber laser, the measured area $R_s = 7.32$ μm.
Fig. 7.  (a) Relation of bulk material removal rate and scanning line offset (spacing between adjacent raster lines); (b) relation of machined surface roughness and scanning line offset

Fig. 8.  The surface of IN718 machined by laser raster scanning measured by 3D microscope resulted in a roughness of $R_a = 5.96 \, \mu m$

Fig. 9.  A 45° film cooling hole machined on TBC coating by 1ns pulsed fiber laser, a measured roughness is $R_a = 7.32 \, \mu m$
4. Conclusion

In the objective of precision laser micromachining on multiple layers of ceramic/metal (i.e. TBC coated superalloy) using an industrial-grade economic nanosecond-pulsed fiber laser, both numerical modelling and experimental methods were established to study the fundamental relations between the processing parameters and the machining geometric features with SS304, Copper, Inconel 718, and TBC coating samples. Processing parameters are optimized in terms of the maximum material removal rate and machining quality. The width, depth and cross-sectional profile of machined trench were examined and measured to investigate the effects of fluence, beam radius, defocus distance. (1) The trench depth is dependent on the laser peak fluence in a logarithmic relation. (2) The volume removal rate reaches a maximum value when the beam waist exceeds respectively. The FEM model predicted volume removal rate follows the same trend with the variation of beam waist. (3) Surface roughness of laser machined by laser raster scanning is measured as $R_a = 5.96 \mu m$ for IN718 and $R_a = 7.32 \mu m$ for TBC coating.

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