Study on the coupling effect of laser and diamond tool

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Abstract In the process of turning hard and brittle materials with laser in-situ assisted diamond tools, the energy of the laser beam will be lost and the laser heat absorbed by the diamond tools will produce temperature fields and thermal deformations, which will affect the machining accuracy. In order to study the interaction between laser and diamond tool during laser in-situ assisted turning, a finite element model of laser and diamond tool transmission was established using COMSOL Multiphysics, and the energy deposition formed on the rake face under different incident conditions was analyzed. The temperature field changes and the rule of tool tip deformation of diamond tools during laser irradiation are shown. Studies have shown that the greater the negative rake angle of the tool, the greater the power density deposited by the laser on the rake face. When the incident angle of the laser is 20°, the power density of the laser on the rake surface reaches the maximum. Under the laser irradiation, the temperature and the deformation of the tool tip increase with time, and finally reach a steady state. The research provides theoretical basis for improving the precision of laser in-situ assisted diamond processing.

1. Introduction
Laser in-situ assisted single-point diamond is an advanced ultra-precision processing method. The laser directly acts on the high-pressure phase change zone of the material contacting the tool through the diamond tool, which can realize the plastic processing of hard and brittle materials, and improve the surface finish of the material and the tool. Life [1-2]. Laser transmission through the diamond tool will cause a series of complex changes such as refraction, reflection and absorption with the diamond tool, which will cause loss of output laser power [3]. The laser power and spot shape acting on the workpiece material become unpredictable, which makes it impossible to effectively control the laser heat source. Among them, the energy of the reflected and transmitted light waves of the laser irradiated diamond is closely related to the wavelength of the laser, the angle of incidence of the laser, and the degree of polarization of the laser. The energy of the laser penetrating the diamond surface will be partially absorbed by the diamond tool. The tool converts light energy into heat energy through the original absorption of laser energy. The heat will be mainly transferred by heat conduction and heat convection during the diffusion process of the diamond tool. The diamond tool absorbs laser energy and generates heat energy inside it, which in turn causes thermal deformation of the diamond tool, which seriously affects the machining accuracy. This paper establishes a laser transmission model in diamond, the influence of different tool rake angles and different laser incident angles on the laser energy density
deposition on the diamond rake face is analyzed, and the temperature field and tip deformation of the diamond tool during laser transmission are solved.

2. Laser transmission diamond tool modeling

2.1 Transmission physical model

![Figure 1. Transmission model of laser and diamond](image)

The diamond tool is a single-point diamond tool with a circular arc edge, and the tool parameters are shown in Table 1.

| Parameter | Value |
|-----------|-------|
| L (mm)    | 3     |
| h (mm)    | 1.2   |
| h2 (mm)   | 0.2   |
| θ (°)     | -25 -30 -35 |
| β (°)     | -40 -45 10 |

Table 1. Diamond tool dimensions

In order to accurately analyze the transmission process of laser and diamond, the laser is simulated as a beam with energy, the energy distribution is Gaussian, and the power density is expressed as [4]:

\[
I_0 = \frac{P}{\pi r^2} \exp(-2((x-l_1)^2 + y^2) / r^2)
\]

In the formula, \( r \) is the laser radius, and \( l_1 \) is the distance between the mirror and the incident surface.

When the laser irradiates the surface of the diamond tool, part of the laser light will be reflected on the diamond surface, and part of the remaining laser energy will be absorbed, and the other part will be transmitted through the material. According to the conservation of energy:

\[
\frac{E_R}{E_0} + \frac{E_A}{E_0} + \frac{E_T}{E_0} = \rho_R + \alpha_A + \tau_T = 1
\]

In formula (2), \( E_0 \) is the laser energy incident on the surface of the diamond tool; \( E_R, E_A, \) and \( E_T \) are the energy reflected, absorbed and projected by the diamond respectively; and are the corresponding reflectance, absorptivity and projection rate, respectively. The energy absorbed by the laser by the diamond is converted into heat, and the heat is diffused inside the diamond by means of thermal conduction to generate a corresponding temperature field, which satisfies the thermal conduction equation [5]:

\[
\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} (k \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y} (k \frac{\partial T}{\partial y}) + \frac{\partial}{\partial z} (k \frac{\partial T}{\partial z}) + Q
\]

In formula (3), \( \rho, c, \) and \( k \) are the density, specific heat capacity and thermal conductivity of the diamond, \( T \) is the temperature, and \( Q \) is the heat source model of the Gaussian laser injected into the diamond. In the process of laser propagation inside the material, the laser intensity decays exponentially. Combined with the Beer-Lambert law, the heat source model can be expressed as

\[
Q = \alpha_A (1 - \rho_R) I_0 \exp(-\alpha_A x)
\]

In the formula, the absorption rate of \( \alpha_A \) processing material, the relationship between the negative refractive index \( n_i \) of the material and the absorption rate \( \alpha_A \) is:

\[
\alpha_A = \frac{4\pi n_i}{\lambda}
\]
Due to the extremely high thermal conductivity of diamond tools, the heat source deposited by the laser inside the diamond tools diffuses at an extremely fast speed. In precision machining and mechanical design, the classic thermal deformation theory can be used to analyze the thermal deformation of diamond [6].

\[ \varepsilon = L \cdot \alpha \cdot \Delta T \]  (6)

Among them, \( L \) is the diamond tool size; \( \alpha \) is the diamond thermal expansion coefficient; \( \Delta T \) is the temperature difference between the tool and the outside; \( \varepsilon \) is the tool tip deformation. Considering that there is a temperature difference between the surface of the diamond tool and the outside world, there is convection and heat exchange with the environment, and the outward emissivity of the diamond surface is very low, and the external radiation is negligible, so the outward heat flux of the surface in the model is:

\[ Q_0 = h_0(T - T_0) \]  (7)

The heat transfer coefficient between the tool and the outside world is \( h_0=5W/(m^2 \cdot K) \), and the ambient temperature \( T_0=293.15K \). The Gaussian laser beam is irradiated on the surface of the diamond tool, and the laser is incident on the diamond through the air, and the light is emitted from the optically thin medium to the optically dense medium. The reflection coefficient and transmission coefficient of the laser amplitude will change correspondingly with the incident angle. Can use Fresnel formula to describe.

Through the multiphysics in COMSOL Multiphysics, the laser transmission diamond process can be accurately analyzed and calculated. Figure 2 shows the transmission model and meshing model of the simulated laser and diamond tool, and Table 2 shows the thermal properties of diamond in the simulation.

![Figure 2. Transmission Model(a) and Mesh division mode(b)](image)

**Table 2. Thermal physical properties parameters of diamond [7-9]**

| Parameter                                      | Value or expression                      |
|-----------------------------------------------|------------------------------------------|
| Thermal conductivity \( k(W \cdot m^{-1} \cdot K^{-1}) \) | \( 3.39 \cdot 10^7/T^{1.26} \)  |
| Density \( \rho \) (kg \cdot m^{-3} )            | 3515                                     |
| Constant pressure specific heat capacity \( C(J \cdot kg^{-1} \cdot K^{-1}) \) | \( C(T) \)                              |
| Coefficient of heat transfer \( h(W \cdot m^2 \cdot K) \) | 8                                        |
| Absorption rate \( \alpha_s \) (laser with a wavelength of 1064nm) | 0.25                                     |
| Laser radius \( r \) (mm)                      | 0.1                                      |
| Thermal expansion coefficient \( \alpha \) (10^{-6}K^{-1}) | \( \alpha(T) \)                        |

The thermal capacity of free diamond \( C(T) \) and the thermal expansion coefficient \( \alpha(T) \) in Table 2 are shown in Figure 3. The thermal capacity and thermal expansion coefficient of diamond will also increase with the increase of temperature.
3. Numerical simulation results and discussion

3.1 Laser power deposition on tool surface

According to the above physical model, the multi-physics coupling analysis software COMSOL Multiphysics is used to calculate and analyze the energy deposition on the laser diamond surface. In the calculation process, the laser wavelength $\lambda=1064\text{ nm}$, the laser power $P=50\text{ W}$, and the incident laser radius $r=0.1\text{ mm}$.

The laser is incident perpendicularly to the surface of the diamond tool from the air. At this time, the incident angle of the laser is 0°. If the scattering of the laser on the incident surface of the diamond tool is not considered, Fresnel's law shows that the reflected energy of the laser on the diamond tool is the smallest, the most transmitted energy. When the laser passes through the diamond, the diamond will absorb very little energy, and most of the energy will be emitted through the rake face and flank face of the tool, heating and softening the phase change zone of the processed material. Table 3 shows the laser power density deposition on the incident surface and the rake surface when the laser is incident perpendicularly from the back of the diamond tool.

| Laser plane of incidence | Flank | Rake face |
|--------------------------|-------|-----------|
|                          | -25°  | -30°      | -35°  | -40°  | -45°  |
| Laser power density      | 13.23 | 13.07     | 5.46  | 6.38  | 7.55  | 8.39  | 9.19 |

Figure 4 shows the power deposition density on the rake surface and the flank surface when the laser has different incident angles. It can be seen from Figure 4(a) that when the negative rake angle of the tool increases, the power density of the laser when it passes through the rake face will increase. When the rake angle of the tool is constant, as the incident angle increases, the power density of the laser deposition on the rake face of the tool first increases and then decreases. This change is more obvious when the negative rake angle of the tool is small. When the incident angle of the laser is 20°, the rake face of diamond tools with different rake angles can achieve better laser power density deposition. This is because increasing the incident angle can reduce the exit angle of the laser beam when it exits the rake face through refraction inside the diamond. From the curve in Figure 4(b), it can be seen that as the incident angle increases, the laser power density of the laser on the diamond flank decreases. This is because when the laser incident angle increases, the reflected energy of the laser also increases, and the transmitted energy decrease, and the spot area increases, resulting in a decrease in laser power density deposition at the flank surface.
3.2 Diamond tool temperature field
When the laser passes through the diamond tool, the diamond tool will absorb part of the laser energy, and this part of the energy will be conducted in the form of heat inside the diamond. Diamond has small size and high thermal conductivity, so it can be regarded as an isothermal body during laser irradiation. Figure 5(a) is the curve of the weighted average temperature of the diamond knife with time under different powers. Figure 5(b) The diamond tool reaches a steady-state temperature under different laser powers. It can be seen that under the action of the laser, the temperature of the diamond tool gradually rises, and the temperature rise slowly increases with the increase of the laser irradiation time. When the irradiation time reaches 500s, it becomes stable. This is because the temperature rises and the heat exchange between the diamond tool and the outside increasingly, when the heat exchange energy is the same as the laser energy deposition, the temperature reaches a steady state. Under steady-state conditions, the temperature of the diamond tool is proportional to the laser power.

3.3 Thermal deformation of diamond tools at different power
Figure 6(a) and Figure 6(b) respectively show the thermal deformation of the diamond tool tip with time under different power laser irradiation and the thermal deformation of the diamond tool tip after reaching a steady state. Combining Figure 5(a) and Figure 5(b), it can be seen that the deformation of the diamond tool tip is closely related to the temperature of the diamond tool. However, due to the change of diamond thermal expansion coefficient with temperature, the deformation at the tip is not completely proportional to the temperature, which has a good correspondence with theoretical calculation.
4. Conclusion
The transmission physical model of Gaussian laser and diamond tool was established by COMSOL Multiphysics, the transmission law of laser in diamond tool under different power was analyzed, and the temperature field distribution and thermal deformation of diamond tool were solved. Research shows that under the same incident mode, the greater the negative rake angle of the tool, the greater the laser power density deposition on the rake face. When the rake angle of the tool is constant, and the laser incident angle is 20°, the power density of the laser emitted from the rake face is the largest. Under laser irradiation, the temperature difference inside the diamond tool is extremely small. As the irradiation time increases, the temperature and thermal deformation of the diamond tool gradually stabilize.

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