Design of a diamond tool for laser in situ assistance

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Abstract Laser in-situ auxiliary processing is an advanced hard and brittle material processing method. In order to improve the utilization rate of the laser in the processing process and better realize the thermal softening effect on hard and brittle materials, the transmission model of the laser and diamond tools was established by COMSOL, and the laser transmission through the rake face of the ordinary arc-edged diamond tool was analyzed. A diamond tool with laser incident surface parallel to the rake surface is designed. The laser incident surface of this diamond tool is parallel to the rake surface, so that the laser can penetrate the diamond rake surface perpendicularly, which is compared with the ordinary circle. The arc turning tool can significantly improve the beam quality, increase the power density of the laser penetrating the tool, and obtain the temperature field change of the diamond tool during laser irradiation and the rule of tool tip deformation. The research is to improve the laser in-situ assisted diamond tool Machining accuracy provides theoretical basis.

1. Introduction

With the development of science and technology in the fields of optics, aerospace, chip military, etc., various engineering ceramics, quartz, glass and other hard and brittle materials are used more and more widely, and at the same time, higher requirements are put forward for their surface quality [1-3]. Laser in-situ assisted diamond tool turning can directly heat the high-pressure metal phase transition zone generated by the negative rake angle of the tool, realize the toughness processing of hard and brittle materials, and can significantly improve the surface finish and tool life of the processed material [4-5]. Before the laser is heated to soften the processed material, it will produce a series of complex physical processes such as refraction, reflection and absorption with the diamond tool, which will cause loss of laser energy, and also cause the divergence of the laser beam, resulting in uncontrollable laser energy in the processing process [6 ]. The paper analyzes the transmission process of the ordinary arc-edged diamond tool in the laser in-situ assisted processing, and the analysis shows that the ordinary arc-edged diamond tool in the laser in-situ assisted processing will cause the laser beam to diverge when passing through the rake face of the tool, and the power density is reduced . Combined with the principle of laser assisted in situ processing to design a kind of laser parallel to the plane of incidence and rake face of diamond tool, through COMSOL Multiphysics transmission model of the laser and the diamond tool is established, and analyzed the diamond tool under the action of laser of temperature field and thermal deformation of the diamond tool compared with ordinary arc blade diamond tool can reduce the energy loss in the process of laser beam in transmission, improve the power density of laser output and the
beam quality, and can be in the region of the raw workpiece preheating, can reduce material hardness, thus improving the processing quality.

2. Analysis of the transmission process of laser and ordinary arc turning tools

During the cutting process of the laser in-situ assisted diamond tool, the laser will act on the high pressure phase transition zone of the processed material at the tip and rake face through the diamond tool. Due to the irregular shape of the diamond, traditional diamond tools have great limitations on the laser transmission process. As shown in Figure 1, the laser can be incident through the back of the tool and the bottom of the tool, and the laser is refracted on the surface of the diamond tool and emitted from the tip of the diamond tool.

![Figure 1](image-url)

Figure 1. Transmission model of laser and ordinary arc-edged diamond tool (a) Incidence from the back of the tool (b) Incident from the bottom of the tool

Figure 1(a) shows the laser incident from the back of the diamond tool, and Figure 1(b) shows the laser incident from the bottom surface of the diamond tool, and is emitted from the tip of the tool through the refraction of the tool body. 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 angle of incidence. The change rule can be described by the Fresnel formula. The refractive index of the laser in the air $n_1=1$, and the refractive index $n$ in diamond is closely related to the wavelength (nm) of the laser, which can be expressed by the Sellmeier equation [7]:

$$n^2 - 1 = \frac{4.3356 \lambda^2}{\lambda^2 - (106)^2} + \frac{0.3306 \lambda^2}{\lambda^2 - (175)^2}$$  \hspace{1cm} (1)

Laser in-situ assisted diamond tool processing uses a laser with Nd:YAG wavelength and laser radius $r=0.1\text{mm}$, so the refractive index of the laser in the diamond tool is. The relationship between the angle of incidence and the angle of refraction can be described by the law of refraction:

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$ \hspace{1cm} (2)

$$n_1 \sin \theta_3 = n_2 \sin \theta_4$$ \hspace{1cm} (3)

In the formula, the mathematical relationship of the laser transmission route is established, combined with the law of refraction, the relationship between the distance $h_3$ of the incident point from the coordinate O and the incident angle $\theta_1$ is:

$$h_3 = h - L \tan(\arcsin(\frac{n_1}{n_2} \sin \theta_1)) - h_2$$ \hspace{1cm} (4)

Similarly, when the laser is incident from the bottom surface of the diamond tool, the relationship between the distance $h_5$ of the laser incident point coordinate O point and the incident angle $\theta_3$ is:

$$h_5 = L - (h - h_2) \tan(\arcsin(\frac{n_1}{n_2} \sin \theta_2))$$ \hspace{1cm} (5)

In order to accurately analyze the laser transmission process inside the diamond tool under these two different incident modes, the laser is simulated as a beam with energy, and its energy distribution is Gaussian. The power density can be expressed as:
In the formula, $P=50\,\text{W}$ is the laser power, $r=0.1\,\text{mm}$ laser beam radius. After the laser passes through the diamond, it is emitted from the tip of the diamond tool and acts on the high-pressure phase transition zone of the processed material. Because the high-pressure phase change zone is usually located at the contact point between the tool rake face and the tool tip, the study of the laser power density acting on the high-pressure phase change zone of the material is of great significance for processing. When the laser is incident from the back side, the rake angle of the diamond tool for processing hard and brittle materials is usually negative, and the rake angle of the tool is often $-25^\circ$ to $-45^\circ$ [8]. Normally, the laser is incident from the back of the diamond tool in a vertical manner. Figure 2 shows the laser power density when the laser is incident perpendicularly from the back of the tool under different negative rake angles of the tool. It can be seen from Figure 2 that when the laser beam passes through the rake face of the diamond tool, the laser beam will diverge, and the divergence becomes more serious as the negative rake angle of the tool decreases, resulting in a decrease in laser power density and beam quality.

$$I_0 = \frac{P}{\pi r^2} \exp\left(-2\left(x^2 + y^2\right)/r^2\right)$$

(6)

Diamond is a high refractive index crystalline material, and the critical angle of gold in the air is $24.7^\circ$. It can be seen from Figure 3 that when the laser is incident from the back of the diamond tool, and when the laser is incident from the back of the diamond tool and emitted from the tip, the laser is totally internally reflected at the diamond rake face, causing the loss of laser energy.

Figure 2. The power density of the incident laser from the back of the rake face

Figure 3. Laser internal reflection phenomenon on the rake surface

When the laser is incident from the bottom of the diamond tool, the beam divergence caused by the negative rake angle of the tool can be improved. If the laser radius is $r=0.1\,\text{mm}$ and the laser power...
\( P = 50 \text{W}, \) the distance between the diamond tip and the bottom of the diamond tool is \( h_0 = 1 \text{mm}, \) in order to avoid laser Deviation from the diamond tool during transmission, therefore:

\[
h_0 (\tan \theta_4 - \tan \beta) - r \geq 0 \tag{7}
\]

In combination with the law of refraction, the law of refraction shows that \( ^\circ, \) because the greater the incident angle of the laser during transmission, the spot that refracts the laser beam will diverge, so when the incident angle is \( 40^\circ, \) the laser beam can be made to pass through the rake The laser power density reaches the maximum, and the spot quality is the best. Figure 4 shows the power density when the laser is incident from the bottom at an angle of \( 40^\circ, \) when the laser passes through rake faces with different negative rake angles. By comparing with Figure 3, this incident method can reduce the divergence of the laser beam and increase the spot power density. However, in this incident mode, due to the larger incident angle, the laser spot area will still become larger during the laser transmission process, and the power density will also be reduced. This incident method is easy to cause the laser and the knife The shank interferes, which is not conducive to processing.

![Figure 4](image)

Figure 4. The power density of the bottom incident laser when passing through the rake face

3. Diamond tool design and perspective model for laser in-situ assistance

Due to the limitations of ordinary arc-blade diamond tools in the laser in-situ assisted machining process, a diamond tool structure for laser in-situ assist is designed. Figure 5(a) shows the diamond tool structure, and Figure 5(b) shows Transmission model of laser and diamond tools. The rake surface of this diamond structure is parallel to the bottom surface of the diamond, and the bottom of the tool handle is provided with a groove. This structure allows the laser beam to be injected perpendicularly from the bottom surface of the diamond tool, directly from the tip of the diamond tool, and the emitted beam is perpendicular to the front The knife surface can reduce the laser energy loss caused by the Fresnel effect on the surface of the diamond tool. This diamond tool structure enables the laser to act perpendicularly to the high-pressure metal phase transition zone of the material. At the same time, the laser beam that does not act on the metal phase transition zone can also pass through the rake face of the diamond tool to preheat the processed material and improve the material softening efficiency.
3.1. Analysis of the power density and beam quality of the laser penetrating the rake face of the tool

Figure 6 shows the power density when the laser radius is $r=0.1\text{mm}$ and the laser power $P=50\text{W}$ through the rake face of diamond tools with different negative rake angles. By comparing the two different incident methods of ordinary arc diamond tools, the laser can still maintain a good spot quality when passing through the rake face of this diamond tool. The power density of the laser at the tool tip is also greatly improved compared to ordinary arc turning tools. The spot size is the output spot size. It is easier to control during processing. The transmission process reduces the Fresnel reflection of the laser on the diamond surface and improves the energy transmission efficiency of the laser in the diamond tool.

3.2. Thermal temperature field of diamond tool

When the laser passes through the diamond tool, the diamond tool has a very large heat transfer coefficient and strong thermal conductivity, and the temperature will be quickly transmitted inside the diamond tool, so the diamond tool will become an isothermal body. Figure 7(a) of diamond is the curve of the weighted average temperature of diamond knife with time under different powers. Figure 7(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, and the lower the laser power density, the earlier it reaches the steady state. Under steady-state conditions, the temperature of the diamond tool is proportional to the laser power.

Figure 7. Diamond tool temperature under different power (a) changes with time (b) At steady state

3.3. Thermal deformation of diamond tools under different powers

Figure 8(a) and Figure 8(b) 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 it reaches a steady state. Combining Figure 7(a) and Figure 7(b), it can be seen that the deformation of the diamond tool tip is closely related to the temperature of the diamond tool, but the deformation of the tool tip due to the change of the thermal expansion coefficient of diamond with temperature, the deformation and temperature at the tool tip are not completely consistent. This is because the coefficient of thermal expansion of diamond increases with increasing temperature.

Figure 8. At different power tool deformation changes (a) Change with time (b) At steady state

4. Conclusion

The transmission physical model of Gaussian distributed laser and ordinary diamond tool was established by COMSOL Multiphysics. The laser will diverge significantly when passing through the ordinary arc-edged diamond tool, and when the laser is incident from the back of the diamond, it will form an inner surface on the rake face. The emission phenomenon causes the loss of laser energy. According to the laser in-situ assisted diamond tool processing method, a diamond tool with the laser
incident surface parallel to the rake surface is designed. The analysis shows that this diamond tool will not cause the laser beam divergence during the laser transmission process, and the energy transmission efficiency improve, the laser penetrates the diamond tool to also preheat the materials in the non-processing area, improving the processing efficiency. The temperature field and thermal deformation of the diamond tool under the action of laser are solved. The results show that the temperature and the deformation of the tip of the diamond tool gradually rise under the action of laser, and increase with the increase of laser power, reaching a steady state at 400s.

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