Mathematically modeling of water jet-assisted ultraviolet-laser machining of thermal barrier coatings

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Abstract. Focusing on the problems that micro-structures of thermal barrier coatings have recast layer and micro-cracks, a new technology of water jet-assisted ultraviolet-laser machining is presented in this study. Ultraviolet laser beam in the water jet is directly focused on the surface of thermal barrier coatings. Micro-structures of thermal barrier coatings are etched by the photochemical effect. Meanwhile, water jet effectively cleans the etched material. Therefore, it is realized that micro-structures of thermal barrier coatings has no recast layer to improve machining quality. The cooling effect of water jet in the ultraviolet-laser machining is considered. Temperature field model, flow field model and the coupling relation model of water jet-assisted ultraviolet-laser machining are built. Moreover, the process of numerical simulation is designed and the results of simulation process are analysed to reveal the forming law. The validity of the model is verified by experiment.

1. Introduction
At present, the inlet temperature of turbine is limited by the material of blade and the improvement of aeroengine performance is restricted. However, the high performance index is achieved by new methods. For instance, technology of thermal barrier coatings (shortly called TBCs) have good performance at cooling effect, high temperature oxidation resistance and corrosion resistance. The thickness of YSZ ceramic coatings is 0.2mm to 0.4mm, so the surface temperature of blade is reduced by 100 degrees centigrade to 150 degrees centigrade [1]. The service life and stability of blade is determined by machining quality of micro-structures of TBCs. Therefore, they are micro-structure devices which are difficult to be machined.

In the manufacturing technologies of nonmetallic micro-structures such as YSZ ceramic coatings, laser machining and other non-traditional machining were more and more frequently applied. Femtosecond laser machining fabricated micro-holes on the silica coated with aluminum film. Micro-cracks and recast layer were not on the edge of holes, so machining quality was improved [2]. However, its efficiency was much lower than nanosecond laser machining. Micro-holes were machined by picosecond pulse laser on the YSZ ceramic coatings. Ceramic chip was not attached to the wall of hole and thermally induced defects like recast layer were avoided. However, plasma impact force in the machining acted on ceramic coatings and made them generate micro-cracks [3]. The cooling effect of water jet in the ultraviolet-laser machining is considered. Temperature field model, flow field model and the coupling relation model of water jet-assisted ultraviolet-laser machining are built. The process of numerical simulation is designed and the results of simulation process are analysed to reveal the forming law. The validity of the model is verified by experiment.

2. Mechanism of water jet-assisted ultraviolet-laser machining
The technology of water jet-assisted ultraviolet-laser machining is shown in Figure 1. Ultraviolet laser beam in the water jet is directly focused on the surface of TBCs. Ultraviolet laser whose power density is larger than 10⁶W/cm² illuminates TBCs. An electron in the ground state simultaneously absorbs more than two photons and leaps into the excited state. The multiphoton absorption occurs. The molecule bond of TBCs materials is directly destroyed. Micro-structures of TBCs are etched by the photochemical effect. The formation of recast layer is avoided to improve machining quality. Meanwhile, the washing by high velocity water jet effectively cleans the etched material. The water jet duly takes the heat energy away from the machining zone in the laser pulse interval. The heat affected zone is reduced.

![Figure 1 The technology of water jet-assisted ultraviolet-laser machining](image)

The mathematical model of water jet-assisted ultraviolet-laser machining

3. Mathematical model of water jet-assisted ultraviolet-laser machining

The cooling effect of water jet in the ultraviolet-laser machining is considered. Temperature field model, flow field model and the coupling relation model of water jet-assisted ultraviolet-laser machining are built. It provides theoretical basis for the numerical simulation system. Sections, subsections and subsubsections.

3.1. Temperature field model of ultraviolet-laser machining in the water jet

Thermal conductivity property in the macroscopic material is analyzed by Fourier's law of heat conduction. Electron-lattice system absorbs ultraviolet laser energy on the etching area, the temperature of which goes up. After temperature gradient is produced between the etching area and the non-etching area, heat transfers from high temperature zone to low temperature zone in the material. Therefore, the problem that double-temperature model cannot describe heat conduction process in the macroscopic material is solved.

Temperature field model of ultraviolet-laser machining in the water jet is shown in Figure 2.
Heat conduction process in the TBCs materials is corresponding to Fourier's law of heat conduction. The temperature field model of water jet-assisted ultraviolet-laser machining is as follows.

\[ \rho \frac{\partial T(x,z,t)}{\partial t} = K \frac{\partial^2 T(x,z,t)}{\partial x^2} + K \frac{\partial^2 T(x,z,t)}{\partial z^2} \] (1)

In the formula, \( \rho \) is density of TBCs, \( c \) is specific heat of TBCs, \( K \) is coefficient of thermal conductivity of TBCs.

The initial temperature on the boundary of ultraviolet laser machining is as follows.

\[ T(x,z,t=0) = T_0 \] (2)

The heat flux density on the boundary of ultraviolet laser machining is as follows \([4,5]\).

\[ q = \eta A \frac{Q}{\pi r^2} EXP\left(-\frac{x^2}{r^2}\right)EXP\left(-u(\lambda)l\right) \] (3)

In the formula, \( \eta \) is revised coefficient of formula, \( A \) is absorption rate of TBCs materials on ultraviolet laser, \( Q \) is ultraviolet laser pulse peak power, \( r \) is laser beam waist radius, \( \mu(\lambda) \) is attenuation coefficient of ultraviolet laser in the water, \( l \) is laser transmission length in the water.

The condition of convection heat transfer of water jet on the boundary of ultraviolet laser machining is as follows \([6,7]\).

\[ -K \frac{\partial T(x,z,t)}{\partial x} - K \frac{\partial T(x,z,t)}{\partial z} = h(T - T_0) \] (4)

In the formula, \( h \) is convection heat transfer coefficient of water jet, \( T \) is material surface temperature after ultraviolet laser machining.

By the above formulas, temperature field distribution on the surface of material in the ultraviolet laser machining time is evaluated. The new machining boundary is obtained by the removal of material above the melting point of TBCs.

3.2. Flow field model of water jet

For water jet on the surface of TBCs, the following assumptions are put forward.

- water jet is constant and incompressible fluid.
- The change of medium temperature and the energy dissipation caused by temperature difference in the machining process is neglected. The flow of water jet is constrained by mass conservation law and momentum conservation law.

Flow field model of water jet is shown in Figure 3.
This study uses the standard k-ε model to analyze flow field distribution of water jet on the surface of TBCs. The model is as follows \(^{(8)}\)

\[
\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho u_i k)}{\partial x_i} = \frac{\partial}{\partial x_i} \left[ \left( \mu + \mu_t \right) \frac{\partial k}{\partial x_i} \right] + G_k - \rho \varepsilon \quad (5)
\]

\[
\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho u_i \varepsilon)}{\partial x_i} = \frac{\partial}{\partial x_i} \left[ \left( \mu + \mu_t \right) \frac{\partial \varepsilon}{\partial x_i} \right] + \frac{C_{1\varepsilon}}{k} G_k - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} \quad (6)
\]

\[
\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \quad (7)
\]

In the formula, \(u_i\) is time-averaged velocity; \(\mu_t\) is turbulent viscosity; \(G_k\) is the generation of turbulent kinetic energy caused by the average velocity gradient; \(\varepsilon\) is turbulent dissipation; \(C_\mu, C_{1\varepsilon}, C_{2\varepsilon}, \sigma_k\) and \(\sigma_\varepsilon\) are model constants.

By the above formulas and the boundary condition of inlet pressure, pressure distribution of water jet on the surface of material in the ultraviolet laser machining time is evaluated.

3.3. The coupling relation model of temperature field and flow field

In the machining process, water jet constantly cools the edge of micro-structures. The heat energy is duly taken away from the machining zone in the laser pulse interval. The heat affected zone is reduced. Therefore, the formula of convection heat transfer coefficient is used to describes the coupling relationship of temperature field and flow field.

The formula of convection heat transfer coefficient is as follows \(^{(9,10)}\)

\[
h = \frac{\lambda}{l} \text{Nu} \quad (8)
\]

In the formula, \(\lambda\) is coefficient of thermal conductivity of water, \(l\) is characteristic size of water jet. Thereinto, the formula of nusselt number is as follows.

\[
\text{Nu} = 0.797 \text{Pr}^{1/3} \text{Re}^{1/2} \quad (9)
\]

The formula of prandtl number is as follows.

\[
\text{Pr} = \frac{\mu C}{\lambda} \quad (10)
\]

In the formula, \(\mu\) is dynamic viscosity of water, \(C\) is isobaric specific heat of water.

The formula of reynolds number of water jet is as follows.

\[
\text{Re} = \frac{vl}{\nu} \quad (11)
\]

In the formula, \(v\) is kinematic viscosity coefficient of water.

The velocity formula of water jet is as follows.
\[ V = \sqrt{\frac{2 \cdot P}{\rho}} \]  \hspace{1cm} (12)

In the formula, \( P \) is pressure of water jet, \( \rho \) is density of water.

4. **Experimental verification of water jet-assisted ultraviolet-laser machining**

In the simulation of flow field of water jet, pressure load was applied. Pressure distribution of water jet on the surface of TBCs was evaluated, which was shown in Figure 4. It was acted by pressure of water jet with 3MPa after the first laser pulse. Pressure distribution of water jet is axisymmetrical and uniform. So it is the guarantee of high quality laser machining.

![Figure 4 Pressure distribution of water jet on the surface of TBCs after the first laser pulse](image)

In the simulation of temperature field of ultraviolet-laser machining in the water jet, heat flux load of ultraviolet laser and convection heat transfer load were applied. Temperature field distribution on the surface of TBCs was evaluated, which was shown in Figure 5. It was acted by laser average power with 5.678W after the first laser pulse. The machining boundary after the first laser pulse was shown in Figure 6. The material was removed by ultraviolet laser. Water jet itself did not remove the material, but it effectively cleaned the etched material to improve machining quality. In the machining process, water jet constantly cooled the machining area to reduce the heat affected zone.

![Figure 5 Temperature field distribution on the surface of TBCs after the first laser pulse](image)
Machining parameters of blind hole whose diameter was 0.04mm were shown in Table 1. The experiment material was the metal blade coated with TBCs and the thickness of YSZ ceramic coatings was 0.1mm. The simulation result of inlet diameter was 0.054mm. The experiment result of blind hole inlet diameter of which was 0.048mm was shown in Figure 7. The simulation result was basically consistent with the experiment result. So the validity of mathematical model of water jet-assisted ultraviolet-laser machining was proved by experiment.

| Machining parameter          | Value |
|-----------------------------|-------|
| Laser wavelength (nm)       | 355   |
| Laser average power (W)     | 5.678 |
| Laser pulse width (ns)      | 15    |
| Laser pulse frequency (KHz) | 30    |
| Laser spot diameter (μm)    | 40    |
| Pressure of water jet (MPa) | 3     |

Figure 6 The machining boundary after the first laser pulse

Figure 7 The experiment result of blind hole
5. Conclusion
A new technology of water jet-assisted ultraviolet-laser machining is presented in this study. Ultraviolet laser beam in the water jet is directly focused on the surface of TBCs. Micro-structures of TBCs are etched by the photochemical effect. Meanwhile, water jet effectively cleans the etched material. Therefore, it is realized that micro-structures of TBCs has no recast layer to improve machining quality. The following is a summary of the conclusions.

1. The cooling effect of water jet in the ultraviolet-laser machining is considered. Temperature field model, flow field model and the coupling relation model of water jet-assisted ultraviolet-laser machining are built. It provides theoretical basis for the numerical simulation system.
2. The process of numerical simulation is designed. The system of numerical simulation is established for used the APDL language of ANSYS. The simulation result is basically consistent with the experiment result. So the validity of mathematical model of water jet-assisted ultraviolet-laser machining is proved by experiment.
3. The forming law of water jet-assisted ultraviolet-laser machining is as follows. The material is removed by ultraviolet laser. Water jet itself do not remove the material, but it effectively cleans the etched material to improve machining quality. In the machining process, water jet constantly cools the machining area to reduce the heat affected zone.

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