Experimental Study on Regression Model of Ultraviolet Laser Processing Thermal Barrier Coating Based on Response Surface Method

Yulan Hu\textsuperscript{1}, Guoqiang Liu\textsuperscript{2}, Weiguang Hao\textsuperscript{1}, Yajie Liu\textsuperscript{2}, Zilin Liu\textsuperscript{1}

\textsuperscript{1}School of Information Science and Engineering, Shenyang Ligong University, Shenyang, China
\textsuperscript{2}School of Mechanical Engineering, Shenyang Ligong University, Shenyang, China

Abstract. In view of the non-conductivity and brittleness of thermal barrier coating materials, the problems of conventional electromachining and machining can not be used. The processing technology of thermal barrier coating materials is studied. The regression model of processing technology based on response surface method is established. The influence of process parameters on the experimental results is of great significance in the field of processing key components of ceramic coatings. The main research work of this thesis is as follows: The regression equation based on response surface method is established, the parameters of laser processing and rotary cutting are analyzed, and the influence of processing precision of various process parameters is analyzed. The electrolyte assisted UV laser processing is designed and carried out.

1. Process parameter analysis

Electrolyte-assisted UV laser processing is the photothermal effect of laser and matter, and there are many factors influencing it. In order to obtain a better micropore structure and improve the processing accuracy, it is necessary to analyze the laser processing parameters and the laser cutting parameters. Zirconium dioxide ceramics doped with stabilized cerium oxide are widely used in thermal barrier coating materials in aerospace engineering. Therefore, this paper uses a zirconia ceramic piece workpiece doped with partially stabilized yttria for systematic process experiments.

1.1 Laser processing parameter analysis

In the electrolyte-assisted UV laser processing experiment, parameters such as laser wavelength, laser pulse energy, and laser repetition frequency will directly affect the feasibility and processing accuracy of the processing. Therefore, these parameters are analyzed as follows:

Laser wavelength. When the laser is transmitted in a liquid, the laser energy is attenuated due to the absorption and scattering of the solution, and the Langber Beer's law is followed. The spectrum of the absorption length of the laser of different wavelengths in pure water is shown in Figure 1 [40]. The absorption length of pure water to 355 ultraviolet light is about 5m, which is calculated. The attenuation coefficient of laser at 355nm wavelength in pure water is 0.2 m\(^{-1}\), due to the low-concentration pure salt solution prepared by pure water, laser attenuation and pure water. There is no significant difference in attenuation, so the 355 nm wavelength laser has an attenuation coefficient of 0.2 m\(^{-1}\) in the electrolyte.
Laser pulse energy. The laser pulse energy is a main parameter of the pulsed laser. The energy control of the nanosecond ultraviolet laser used in the experiment is adjusted by changing the laser power factor (PWF), that is, the pulse energy is adjusted in steps of “‰”. Using a laser power meter to measure the variation of laser pulse power with power factor, the curve of the pulse frequency is 30kHz, 60kHz, 80kHz, as shown in Figure 2, if the laser pulse energy is too low, the unit within the processing area will be If the area power density is too small to melt and vaporize the material, laser processing cannot be performed. However, if the laser single pulse energy is too high, a large amount of bubbles will be generated due to excessive laser power density at the focal point per unit area. Large, affecting the processing effect; therefore, the laser power factor should be reasonably selected according to the actual situation, the laser pulse energy should be adjusted, and better processing results can be obtained under the premise of ensuring the processing efficiency.

Figure 2 Repetition frequency 30kHz, 60kHz, 80kHz, pulse energy versus power factor (PWF)
Laser pulse frequency. The 355nm UV laser used in this experimental system has a repetition rate adjustable from 30kHz to 150kHz. When the current is 28A, the chiller is set to 20°C, and the laser power factor (PWF) is 950, the measured curve of the laser pulse energy with the repetition frequency is shown in Figure.3. As the repetition frequency increases, the laser pulse energy decreases. Small, due to the attenuation of the electrolyte, the selection of the repetition frequency is too large, the purpose of removing the laser-based material is lost, and the effect of removing the material cannot be achieved; the repetition frequency is too small, the laser pulse energy is large, and the processing precision cannot be guaranteed.
1.2 Analysis of rotary cutting parameters

The laser galvanometer is used to control the focus of the laser beam to perform the rotary cutting micropore test on the processed sample, and the processing area is rotated and processed by the software system. Among them, the repeated test is repeated in the case where the selected micropore diameter is 0.4 mm. Contrast, select the concentric circular cutting method to machine the small holes. Combined with the characteristics of UV laser processing parameters, the laser cutting speed and the turning distance are analyzed.

(1) Rotating speed. The laser cutting speed has a great influence on the circular hole roundness error and the upper and lower diameter difference. The smaller the turning speed, the higher the overlapping rate of the laser spot, the greater the power density of the laser acting on the material, and the smaller the removal of the small hole material. In the case where the turning distance and the number of processing times are selected, the larger the turning speed, the smaller the spot overlap ratio, and the corresponding material removal amount is reduced.

(2) The cutting distance. The laser cutting distance directly changes the laser spot overlap ratio in the direction of the center of the concentric circle, so that the power density per unit area of the laser processing increases, and the removal amount of the laser increases. Therefore, the larger the laser rotation spacing, the smaller the spot overlap ratio and the less the material removal.

2. Experimental design

In this experiment, according to the laser electrolysis combined micro-machining test basis, the main process parameters laser power factor, pulse frequency, rotary cutting speed and turning distance are selected as the influence factors, which are respectively coded as $x_1$, $x_2$, $x_3$, $x_4$, and above The range of process parameters is as follows: laser power factor: 630~950, laser pulse frequency: 30kHz~46kHz, laser cutting speed: 10mm/s~26mm/s, laser cutting distance: 10μm~42μm. The main process parameters of electrolyte-assisted UV laser processing were horizontally coded by orthogonal test design method as shown in Table 1.

Table 1. Four-factor five-level coding table

| factor                        | Horizontal code / actual value |
|-------------------------------|--------------------------------|
| $x_1$ Laser power factor (%)  | 1  2  3  4  5                   |
| $x_2$ Laser pulse frequency (kHz) | 30  34  38  42  46             |
| $x_3$ Laser rotary cutting speed (mm/s) | 10  14  18  22  26             |
| $x_4$ Laser cutting spacing (μm) | 10  18  26  34  42              |

Figure 3 Laser pulse energy with repetition frequency curve
3. Regression analysis

For the determination of the response value: the upper and lower diameter difference evaluation taper; the upper machining accuracy to evaluate the inlet machining accuracy.

The experimental results were processed by Design Expert 7.1.3 software, and the regression equations of each response value were established, and the influence of process parameters on the experimental results was analyzed.

The regression variance analysis of the upper and lower diameter difference, corresponding to the regression equation, see Formula 1. From the analysis, the upper and lower diameter difference model F value is 3.449409, the corresponding p-value is 0.0015<0.05., the model is established. The regression equation showing the difference of upper and lower diameter is the highest. The first laser cutting speed and the rotary cutting spacing are the highest, the influence on the upper and lower diameter difference is greater, the other items have less effect on the upper and lower diameter difference.

The quadratic regression equation of the difference between the upper and lower diameters:

$$UDDD = 315.19337 - 0.429682 \times x_1 - 14.722614 \times x_2 - 4.027824 \times x_3 + 0.47301 \times x_4 + 0.003035 \times x_1^2 + 0.002044 \times x_1 \times x_2 + 0.003815 \times x_1 \times x_3 + 0.008375 \times x_2 \times x_3 + 0.004222 \times x_2^2 + 0.002044 \times x_1 \times x_4 + 0.001415 \times x_1 \times x_4 + 0.005375 \times x_2 \times x_4 + 0.000183 \times x_1^2 + 0.038195 \times x_2 \times x_4 + 0.041222 \times x_3 \times x_4 + 0.000183 \times x_1^2 + 0.038195 \times x_2^2 + 0.075584 \times x_3^2 + 0.005375 \times x_4^2$$  (1)

Analysis of the regression variance of the machining accuracy. The corresponding regression equation is shown in Formula 2. The analysis shows that the F value of the upper machining accuracy model is 3.252048, the corresponding p-value is 0.0023<0.01, and the model is established, which indicates that the regression equation of machining precision is the most significant. The first time laser power factor, the pulse frequency and the rotation tangent spacing interaction term showed the highest remarkable, has the main influence to the upper processing precision. The interaction of pitch interaction, spin-cutting speed and rotation-tangent spacing and power factor two are generally significant, and the accuracy of the machining is generally affected; the remaining items have less impact on the machining accuracy.

The quadratic regression equation of the upper machining accuracy:

$$UMA = 235.758597 + 0.765607 \times x_1 + 2.653537 \times x_2 + 0.886572 \times x_3 + 36.151811 \times x_4 + 0.003582 \times x_1^2 + 0.003612 \times x_1 \times x_2 + 0.004432 \times x_1 \times x_3 + 0.082021 \times x_2 \times x_3 + 0.088884 \times x_2^2 + 0.07359 \times x_3^2 + 0.00047 \times x_1 \times x_4 - 0.043922 \times x_2 + 0.139001 \times x_3 + 0.009639 \times x_4$$  (2)

4. Impact analysis

The effect of process parameters on the difference between the upper and lower diameters is shown in Figure 4.

(1) The difference in upper and lower diameters substantially decreases as the laser power factor increases. At the same time of the increase of the laser power factor, the average laser power increases, and the laser spot size does not change, which will increase the erosion ability of the laser processing, and the ejection capability of the melt is enhanced, thereby reducing the difference in the upper and lower diameters.

(2) The difference between the upper and lower diameters increases slightly with the increase of the laser pulse frequency. The increase of the laser pulse frequency leads to an increase in the laser spot overlap ratio in the laser cutting direction, an increase in the pulse frequency, an increase in the laser erasing ability, an increase in the diameter of the upper surface circle, and a diameter of the lower surface due to the attenuation of the electrolyte. The size does not have a large influence on the diameter of the upper surface circle, resulting in a small increase in the difference between the upper and lower diameters.

(3) The difference in upper and lower diameters increases as the laser cutting speed increases. Under the same conditions of laser pulse frequency and spot size, the larger the laser cutting speed is, the smaller the laser spot overlap ratio are, the smaller the laser power density is, and the corresponding laser erosion amount decreases, so the upper and lower diameter differences increase.
(4) The difference between the upper and lower diameters generally increases as the distance between the laser concentric circles increases. The distance between the concentric circles of the laser increases, the spot overlap ratio on the trajectory is reduced, and the average power density of the laser is reduced, thereby reducing the difference in diameter between the upper and lower sides.

![Figure 4: The influence of process parameters on the diameter difference between upper and lower](image)

The effect of process parameters on the upper machining accuracy is shown in Figure 5.

(1) As the laser power factor increases, the upper machining accuracy increases first and then decreases. As the laser power factor increases, the average laser density will increase. As the diameter of the laser spot is almost constant, the amount of laser erosion increases. At the same time as the material is eroded, the effect of the laser cavitation bubble and the attenuation of the laser transmission by the electrolyte. Sex, the upper machining accuracy will increase first and then decrease.

(2) The upper machining accuracy increases as the laser pulse frequency increases. When the laser pulse frequency is increased, the spot overlap ratio in the laser cutting speed direction will increase, the average laser power density in the same processing area will increase, and the laser erasing ability will be enhanced, so that the upper machining accuracy is increased.

(3) As the laser cutting speed increases, the upper machining accuracy increases slightly and then decreases. Under the same laser pulse frequency and spot size, the larger the laser cutting speed, the smaller the spot overlap ratio in the direction of the rotation, at which time the size of the laser erosion plays a leading role, and the upper machining accuracy will increase slightly. When the spot overlap ratio is reduced to a uniform track rotation, a better machined hole shape can be obtained, thereby reducing the upper machining accuracy.

(4) The upper machining accuracy generally decreases as the pitch of the laser concentric circles increases. As the distance between the concentric circles of the laser increases, the laser spot overlap ratio on the concentric circular track decreases, and the laser power density decreases, thereby reducing the upper machining accuracy.

![Figure 5: The influence of process parameters on the machining accuracy](image)

5. Conclusion

Based on the mechanism of electrolyte-assisted UV laser processing thermal barrier coating materials, the main experimental parameters of the experiment were analyzed firstly. Secondly, the electrolyte-assisted UV laser processing was designed and carried out, and the regression equation based on
experimental results was established. Finally, the influence of various process parameters on the experimental results is analyzed. The processing rules of thermal barrier coatings are summarized, and the optimal experimental scheme is efficiently found to provide an effective method for high-quality thermal barrier coating microstructure processing. It has important significance and application prospects in the processing and manufacturing of key components such as aviation and aerospace with thermal barrier coating.

Acknowledgments
The work was supported by the National Natural Science Foundation of China(NO.61672360).

References
[1] LI Xiaoyu, SUN Huilai, ZHAO Fangfang, NIE Xiaoju. Research on parameter optimization design of femtosecond laser processing SiC model[J]. LASER & IR, 2016, 46(08): 948-952.
[2] Jia Wei, Wang Qingyue, Fu Xing, Hu Xiaotang. Application of Femtosecond Laser in Material Micromachining[J]. Chinese Journal of Quantum Electronics, 2004, (02): 194-201.
[3] Lai Hongkun. Laser micromachining of metal and thermal barrier coatings using 532nm nanosecond fiber laser [D]. [Master's thesis]. Shanghai: Shanghai Jiaotong University, 2014.
[4] Lai Hongkun, Qi Huan. Laser micromachining of metal and thermal barrier coatings using 532nm nanosecond fiber laser [J]. China Laser, 2013, 40(08): 52-57.
[5] ZHAN Caijuan, LI Changzhen, WANG Yuli. Heat transfer analysis and numerical simulation of water jet guided laser drilling[J]. Journal of Applied Lasers, 2009, 29(05): 415-418+422.
[6] Zhang Hua,Xu Jiawen. Modeling and Experimental Investigation of Laser Drilling with Jet Electrochemical Machining[J]. Chinese Journal of Aeronautics,2010,23(4):.
[7] Nguyen M D, Rahman M, Wong Y S. Simultaneous micro-EDM and micro-ECM in low-resistivity deionized water[J]. International Journal of Machine Tools & Manufacture, 2012, 54-55: 55–65.
[8] Hu Xiaotong, Huan Rong. The current situation and development of China's laser industry [J]. Applied Laser, 1990, (03): 97-100.
[9] Avanish Kumar Dubey, Vinod Yadava. Laser beam machining—A review [J]. International Journal of Machine Tools & Manufacture 48 (2008): 609-628.
[10] He Fei, Cheng Ya. Femtosecond laser micromachining: a new frontier in the field of laser precision machining [J]. China Laser, 2007, (05): 595-622.
[11] Xie Yijiang, Li Dianjun, Zhang Chuansheng, Guo Weihai. Acousto-optic QC_2 laser[J]. Optics and Precision Engineering, 2009, 17(05): 1008-1013.
[12] CHEN Zhiling, SHI Tielin, LIU Sheng, XIONG Liangcai. Excimer laser microfabrication technology and its application[J]. Progress in Laser and Optoelectronics, 2004, (02): 47-53.