

Effect of Specimen Size on Laser Scribing Width and Depth of Al₂O₃ Ceramics: Experiment and Numerical Simulation

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Abstract. To obtain high precision and quality of laser ceramic scribing, people should consider the laser scribing parameters and the geometries of specimen size. In this paper, the effect of specimen size on laser scribing width and depth of Al₂O₃ ceramics was simulated and verified by using ANSYS software and Diode Pumped Solid State (DPSS) laser scribing, respectively. The calculated results and the experimental results all proved that the specimen size had important effect on laser scribing width and depth due to the heat accumulation effect during laser scribing.

1 Introduction

The ceramic materials have been widely used in communications, automotive, power electronics, aerospace and medical fields due to its excellent properties such as light weight, high hardness, wear resistance and corrosion resistance. However, it is very difficult to process because of its high brittleness and high hardness. It is well known that grinding used diamond grinding wheel is the main processing method for ceramic materials, and it has the disadvantages of high cost and low efficiency. Moreover, only simple flat or circular-arc surface parts can be processed and complicated cavity or complex profile cannot be processed.

With the development of laser technology, the laser scribing technology has been widely used to replace the traditional mechanical method, especially for the high precision machining. For example, laser scribing can undertake precision machining of ceramics, make narrow groove and controllable process circular, sharp corners and other irregular shapes [1-3].

However, so far, the laser ceramic scribing was mainly focused on the optimization of laser processing parameters and the numerical simulation of temperature field. Few literatures involved the effect of specimen geometries on the depth and width of laser

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ceramic scribing. Different specimen geometries can cause heat accumulation in different degree, and then affect the scribing depth and width, thus affect the scribing geometric accuracy. Therefore, it is necessary to carry out the research work. In this paper, the effect of specimen size on laser scribing width and depth of Al_2O_3 ceramics was simulated and verified by using ANSYS software and Diode Pumped Solid State (DPSS) laser scribing , respectively.

2 Experimetal

Laser scribing of Al_2O_3 ceramics was carried out by the RF-P50S DPSS laser. The specimen sizes are $7 \times 1.5 \times 0.35 \text{ mm}^3$ (sample A) and $7 \times 10 \times 0.35 \text{ mm}^3$ (sample B). The laser scribing width and depth were measured by the VHX-1000C three-dimensional super depth field microscope. The laser scribing parameters are given as follows: laser power P is 50 W, pulsed laser frequency is 20 kHz, air pressure of blowing is 0.35 MPa, laser scribing speed V is 4 mm s^{-1} , laser beam radius r is 0.017 mm.

3 Mathematical Model

To build up an appropriate mathematical model, the following assumptions should be used:

(1) The laser beam moves with constant velocity V;(2) The Al_2O_3 ceramics is isotropic;(3) The density, specific heat capacity, thermal conductivity and convection coefficient of the Al_2O_3 ceramics remain constant with temperature;(4) Phase changes from solid to vapor occur instantaneously, neglecting formation of liquid residual; (5) Laser radiation within the groove is neglected.

During laser scribing, the laser heat source moves with velocity V on the surface of Al_2O_3 ceramics. The heat transfer equation can be expressed as:

$$\rho c \frac{\partial T}{\partial t} = k \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + Q(x, y, z, t) \quad (1)$$

Where k is the thermal conductivity, ρ is the density, c is the heat capacity of the Al_2O_3 ceramics, T is the temperature function and $Q(x, y, z, t)$ is the heat generation rate in the body (Q was taken as zero when simulation).

Due to the laser can penetrate the alumina ceramic, the absorption of the laser in the Al_2O_3 ceramics is the Beer-Lambert bulk absorption rather than surface absorption. And the laser heat source Q_0 can be loaded in the form of heat production rate in the Al_2O_3 ceramics, which can be expressed as:

$$Q_0 = \frac{2P}{\pi r^2} \cdot \frac{1}{(1 - \exp(-2))} \cdot a \cdot \exp(-a \cdot z) \cdot (1 - r_f) \cdot \exp\left(-\frac{x^2 + y^2}{r^2}\right) \quad (2)$$

P is laser power, r is the laser beam radius, a is the absorption coefficient, r_f is the surface reflectivity. The initial condition is written as:

$$T(x, y, z, 0) = T_0 = 25^\circ C \quad (3)$$

With the laser beam scanning, the assisted gas flows through a coaxial nozzle to the workpiece surface, so the top surface convective boundary condition is:

$$k \left(\frac{\partial T}{\partial x} n_x + \frac{\partial T}{\partial y} n_y + \frac{\partial T}{\partial z} n_z \right) = h_f (T_0 - T) \quad (4)$$

Where h_f is the forced convection heat transfer coefficient. Except for the plane of symmetry and bottom surface, the workpiece in the natural environment has the natural convection, the corresponding boundary condition is:

$$k\left(\frac{\partial T}{\partial x}n_x + \frac{\partial T}{\partial y}n_y + \frac{\partial T}{\partial z}n_z\right) = h(T_0 - T). \quad (5)$$

Where h is natural convection heat transfer coefficient.

The temperature distribution can be obtained by simultaneous equations (1)-(5). And the laser scribing width and depth of Al_2O_3 ceramics are defined as the part which the temperature is more than the melting point (2030°C) of Al_2O_3 ceramics.

Laser beam moves from the midpoint of the narrow side in the Al_2O_3 ceramics plate, a three-dimensional finite element model was set up, the mesh generation of different samples can be seen in Fig. 1. To meet the accuracy requirement and reduce computing time, the gradient mesh generation was used. That is, the laser heating region size is $7 \times 0.05 \times 0.35 \text{ mm}^3$ and the mesh size is $0.01 \times 0.01 \times 0.035 \text{ mm}^3$. The intermediate part region size is $7 \times 0.1 \times 0.35 \text{ mm}^3$ and the mesh size is $0.01 \times 0.05 \times 0.035 \text{ mm}^3$. The outermost region size is $7 \times 0.6 \times 0.35 \text{ mm}^3$ (sample A) or $7 \times 4.85 \times 0.35 \text{ mm}^3$ (sample B) and the mesh size is $0.01 \times 0.2 \times 0.035 \text{ mm}^3$.

Based on the finite element software ANSYS APDL command flow, the temperature field was simulated. Eight node hexahedral unit is selected (SOLID 70), and forced convection coefficient is loaded on the surface effect unit (SURF 152). In the sequential thermal analysis, specimen A uses 77000 hexahedral elements while 84821 nodes are used. The specimen B uses 246400 hexahedral elements and 254463 nodes. The calculating parameters used in this paper are given in Table 1 [4-7].

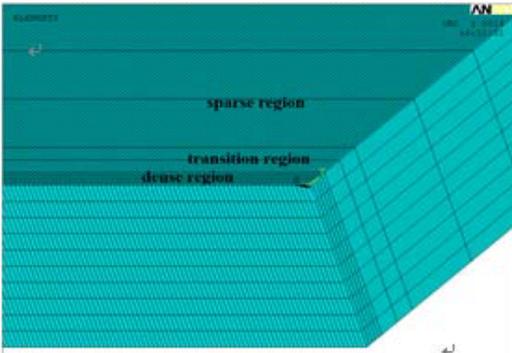
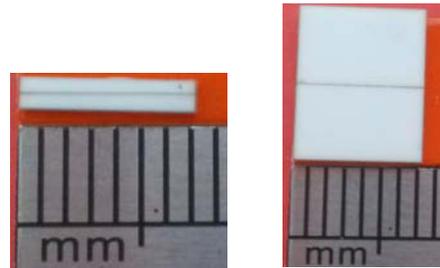


Fig. 1 Local meshing of sample A or sample B



(a) sample (b)sample

Fig.2 Whole photographs of different Al_2O_3 ceramics plate after laser scribing

TABLE 1 THE SIMULATED PARAMETERS

Calculating parameters	Values
Density ρ ($Kg \cdot m^{-3}$)	3720
Specific heat capacity C ($J \cdot Kg^{-1} \cdot ^\circ C^{-1}$)	880
Thermal conductivity k ($W \cdot m^{-1} \cdot ^\circ C^{-1}$)	25
Melting temperature T ($^\circ C$)	2030
The forced convection heat transfer coefficient h_f ($W \cdot m^2 \cdot K^{-1}$)	3000
The natural convection heat transfer coefficient h ($W \cdot m^2 \cdot K^{-1}$)	20
Reflectivity r_f	0.79
Absorption coefficient a (m^{-1})	6000

4 Results and Discussion

The experiment and simulation for laser straight scribing of alumina are carried out. Fig. 2 shows the whole photographs of Al_2O_3 ceramics plate after laser scribing. Fig. 3 shows the picking up temperature points of different samples. Fig. 4 and Fig. 5 are the width photographs and the depth photographs of different samples at $L=4.0$ mm after laser scribing, respectively. Comparatively speaking, the width and the depth of sample A are bigger than that of sample B, respectively.

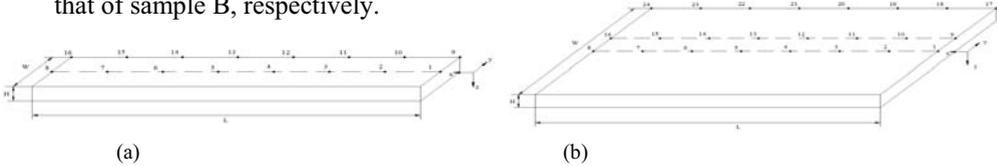


Fig. 3 Picking up temperature points for (a) sample A, (b) sample B

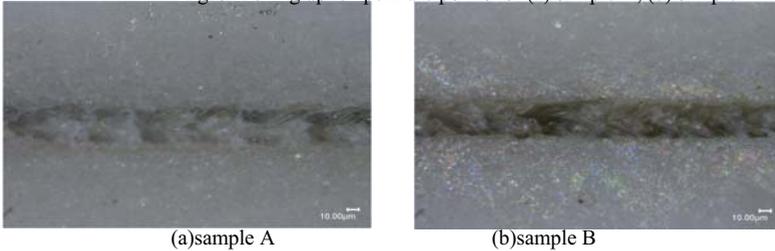


Fig. 4 Width photographs of different samples after laser scribing at $L=4.0$ mm

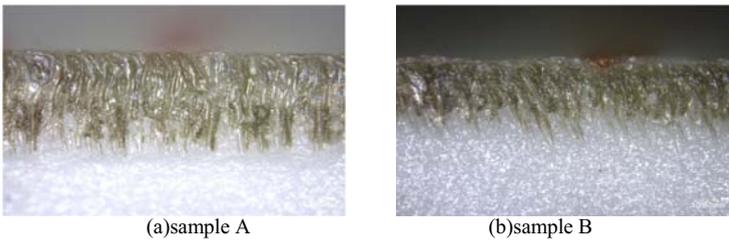


Fig. 5 Depth photographs of different samples after laser scribing at $L=4.0$ mm

Fig. 6 is the comparison between the experimental results and the calculated results of groove width and groove depth for different samples after laser scribing. From Fig. 6(a), we can see that with the increase of laser scribing length, the measured width of sample A is bigger than that of sample B and the calculated width of sample A is also bigger than that of sample B. From Fig. 6(b), we can see that with the increase of laser scribing length, the measured depth of sample A is bigger than that of sample B and the calculated depth of sample A is also bigger than that of sample B. The explanations of the results can be used the heat accumulation effect.

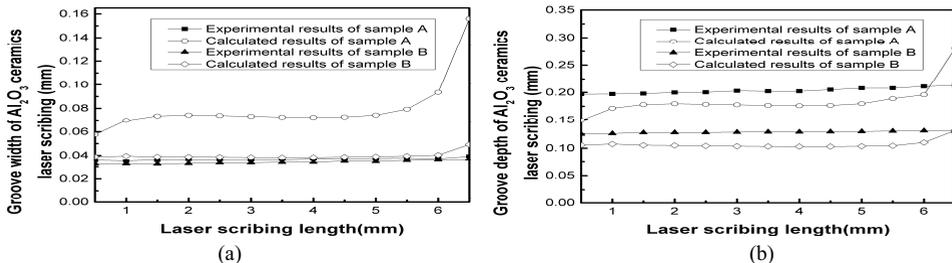


Fig. 6 Comparison between the experimental results and the calculated results of groove width (a) and groove depth (b) for different samples

Fig. 7 shows the curve of the calculated maximum temperature vs laser scribing time at

fixed position (4.0 mm,0,0) for sample A and sample B. From Fig. 7, we can see that there is a serious heat accumulation phenomenon during laser scribing and the calculated maximum temperature for sample A at fixed position (4.0 mm,0,0) is bigger than that for sample B. That is to say, during laser scribing, the heat accumulation will become more and more obvious when the laser scribing length increases, and will result in the increase of the width and depth of laser scribing according to our definition (Fig. 6). In the other hand, the specimen size is small, the heat accumulation caused more serious (Fig.8), the width and depth of laser scribing is more big. So, the width and depth of laser scribing for sample A is bigger than that of sample B (Fig.6). In conclusion, the specimen size has an obvious effect on the laser scribing width and depth of Al_2O_3 ceramics.

5 Conclusions

- (1) The calculated results are in agreement with the experimental results.
- (2) The specimen size has obvious effect on the laser scribing width and depth due to the heat accumulation.

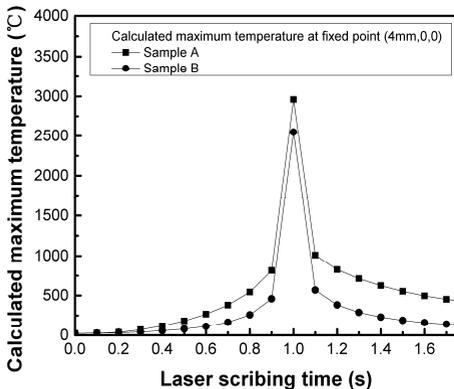


Fig. 7 Calculated maximum temperature vs laser scribing time at fixed position (4.0 mm,0,0) for sample A and sample B

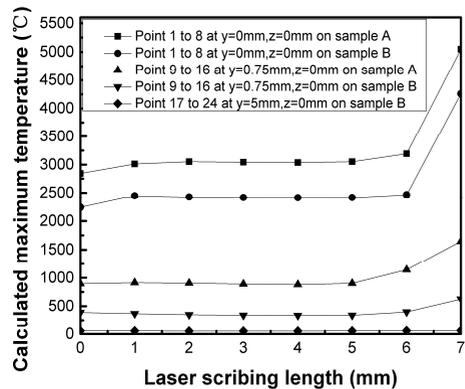


Fig. 8 Calculated maximum temperature vs laser scribing time at different picking up temperature points

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