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Study on the diamond tool drilling of engineering ceramics

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Abstract

A method for drilling holes in engineering ceramics by using a diamond tool has been developed. In this method, a drilling tool rotates with fixed abrasives. The machining mechanism of drilling based on the fracture mechanics concept is analyzed, and a new theoretical model of the material removal rate is proposed. According to this model, the material removal rate increases in accordance with the increase of the static load applied, the rotational speed of the drilling tool, and the grain size of the abrasive. Selecting 99.5% Al_2O_3 ceramics as the workpiece material, experiments have been carried out. The results show that diamond drilling is an effective method for machining engineering ceramics. © 2002 Published by Elsevier Science B.V.

Keywords: Engineering ceramic; Diamond tool; Drilling; Machining mechanism

1. Introduction

Engineering ceramics have numerous excellent physical and mechanical properties: high hardness, high thermal resistance, chemical stability, and low thermal and electrical conductivity, to name but a few. Because of these special qualities, engineering ceramics are expected to be used increasingly in a number of high-performance applications ranging from electronic and optical devices to heat- and wear-resistant parts [1–3]. Until today, their applications have mostly been limited to electronic and optical devices. One reason is to be found in the limitation on the forming process prior to sintering, which restricts the generation of complex geometry and makes it difficult to ensure adequate accuracy and surface finish. There is also a considerable deficit in terms of the production or machining of more complex geometries in the hardened post-sintering state, with limitations on either the performance or the forming capacity of the majority of the processes in current use.

Machining engineering ceramics to final dimensions by conventional methods is extremely laborious and time consuming. Tight tolerances and dimensions with acceptable surface and sub-surface damage are something only attainable at great cost. Thus research into the areas of more efficient material removal processes have been beginning to gather momentum in recent years, especially in the ways and means of reducing the occurrence of faults or cracks in the sub-surface of the machined ceramics [4–6].

A kind of machining method for drilling holes in engineering ceramics by using a rotary diamond tool is proposed in this paper. It can increase the material removal rate, and improve the surface finish.

This paper intends to further the understanding of the basic mechanisms the diamond tool drilling of ceramics and thus to enable the prediction of the material removal rate in terms of the static load applied, the grain size of the abrasive, and the rotational speed of the drilling tool.

2. The mechanism of diamond tool drilling

The process of diamond tool drilling is shown schematically in Fig. 1. The tool is rotating in the drilling process, the workpiece is stationary. The material removal mechanism has been investigated generally by microscopic observation of the abraded surface. The process of material removal is thought to be similar to that of a single tool cutting in that in all cases material is removed by an individual tool or particle displacing or fracture the work surface. The workpiece material is found to be 'stabbed' off in the form of many minute particles by the abrasive grains grinding.

It is concluded that the removal of engineering ceramic occurs primarily by brittle fracture in diamond tool drilling. To understand this process, it is helpful to study the indentation

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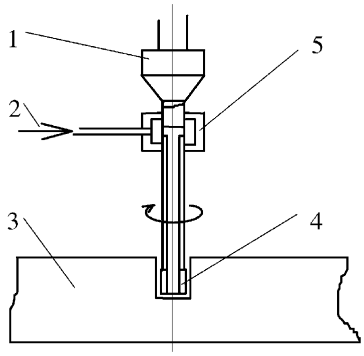

Fig. 1. Schematic diagram of the diamond tool drilling process: (1) chuck, (2) water, (3) workpiece, (4) tool, (5) water jacket.

of brittle materials, because the abrasive grains acting on the workpiece surface are just like indenters.

2.1. Investigation of indentation in ceramics

The deformation and fracture pattern observed under the normal contact of ceramics by a Vickers indenter is illustrated in Fig. 2. Directly under the indenter is a zone of plastic deformation. Two principal crack systems have been identified, which emanate from the plastic zone: median/radial cracks and lateral cracks. The behavior of both types of cracks is effected by residual stresses from the non-uniform plastic deformation in the elastic/plastic material. Radial cracks are initiated by a wedge-like action during loading, and they may continue to propagate during unloading due to residual tensile stresses acting on the crack-tip. Lateral cracks are observed to initiate and propagate by residual stresses only as the indenting load is removed. The initiation and propagation of radial as well as lateral cracks are considered to contribute greatly to the material removal process. As shown in Fig. 2, the initiation and propagation of these radial and lateral cracks at the end lead

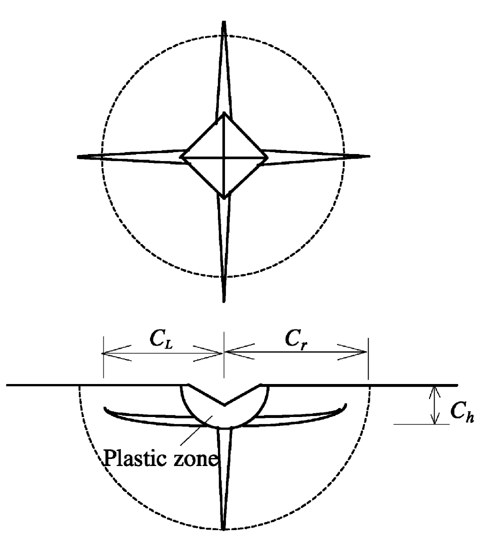

Fig. 2. Localized deformation and fracture of ceramics due to indentation.

to chipping of the brittle material. A critical load P_c for initiating a radial crack is given by [7]:

$$P_c = \alpha \frac{K_{IC}^4}{H_V^3} \quad (1)$$

where α is a dimensionless factor related to the indenter geometry, K_{IC} is the fracture toughness of workpiece, and H_V is the Vickers hardness of the workpiece material.

For the size of the median or radial crack C_r and lateral crack C_L, respectively, the following equations have been derived [8]:

$$C_r = \xi_1 P^{1/2}(H_V^{1/4} K_{IC}^{1/3}) \qquad C_L = \xi_2 \left(\frac{P}{K_{IC}}\right)^{3/4} \quad (2)$$

where P is the load applied, and ξ_1 and ξ_2 are proportional constants.

It is generally regarded that the depth of the lateral crack C_h is proportional to $(P/H_V)^{1/2}$:

$$C_h = \xi_3 \left(\frac{P}{H_V}\right)^{1/2} \quad (3)$$

where ξ_3 is a proportionality constant [9].

It is concluded from these results that the size of the median/radial or lateral crack grows with an increase in the load and with a decrease in the fracture toughness of the workpiece material. Investigations on indentation described so far provide useful information for understanding the practical diamond drilling process of ceramics.

2.2. The relationship between the material removal rate and various parameters

According to the test results of ceramics in indentation, a model of material removal caused by a single abrasive is proposed, as shown in Fig. 3. The model takes into account the linear tangential motion of the abrasive along the surface. Assuming that an individual abrasive grain follows a linear path with a constant depth of cut, the volume of workpiece material removed by an abrasive grain (indenter) under a normal load P is proportional to the dimensions of the lateral crack and the length of travel d. The volume of

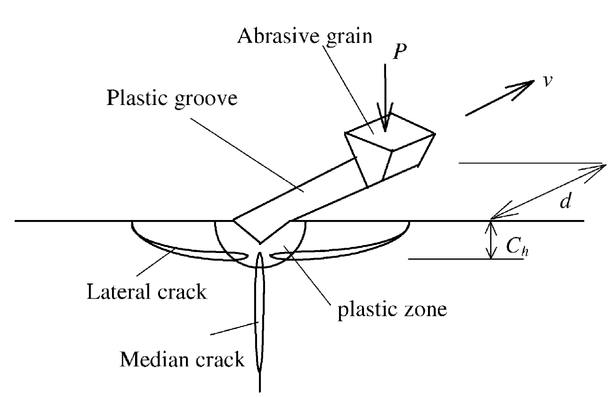

Fig. 3. Schematic model of chip formation.

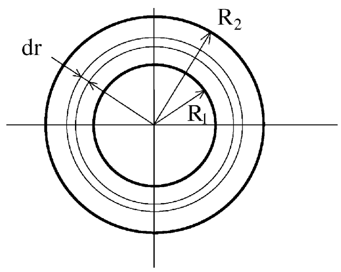

Fig. 4. Schematic diagram of the terminal face of the drilling tool.

removed workpiece material V_0 for one grain is obtained as (see Fig. 4):

$$V_0 = 2C_L C_h d \tag{4}$$

where C_L is the length of the lateral crack, C_h is the depth of the lateral crack, d is the acting distance of the grain.

Then, the material removal rate for one grain is given by:

$$M_{V_0} = 4\pi C_L C_h \omega r \tag{5}$$

where ω is the rotational speed of the tool, and r is the radius of the grain's track.

Assuming that the density of the effective cutting grains is λ, the number of effective grains in area dA (see Fig. 4) is:

$$n = \lambda\,\mathrm{d}A = 2\lambda\pi r\,\mathrm{d}r \tag{6}$$

Then, the material removal rate of the tool is:

$$M_V = \int_{R_1}^{R_2} 8\pi^2 \lambda C_L C_h \omega r^2\,\mathrm{d}r = \frac{8}{3}\pi^2 \lambda C_L C_h \omega (R_2^3 - R_1^3) \tag{7}$$

The number of effective grains in the terminal face of the tool is [10]:

$$N = \lambda A = \frac{K_1}{d_0^2}\left(\frac{6\upsilon_g}{\pi}\right)^{2/3} \pi (R_2^2 - R_1^2) \tag{8}$$

where $A = \pi(R_2^2 - R_1^2)$, R_2 is the external radius of the diamond drilling tool, R_1 is the internal radius of the diamond drilling tool, K_1 is proportionality constant; υ_g is the concentration of abrasive grains, and d_0 the mean diameter of the abrasive grains. Then:

$$\lambda = \frac{K_1}{d_0^2}\left(\frac{6\upsilon_g}{\pi}\right)^{2/3} \tag{9}$$

The load acting on a single abrasive grain is:

$$P = \frac{W}{N} = W\left(\frac{d_0^2}{\pi K_1}\right)\left(\frac{6\upsilon_g}{\pi}\right)^{-2/3} (R_2^2 - R_1^2)^{-1} \tag{10}$$

Substituting Eqs. (2), (3), (9), (10) into Eq. (7):

$$M_V = \frac{8}{3}\pi^{3/4}\xi_1 \xi_2 \omega \left(\frac{d_0^2}{K_1}\right)^{1/4}\left(\frac{6\upsilon_g}{\pi}\right)^{-1/6} \times K_{IC}^{-3/4} H_V^{-1/2} W^{5/4} \frac{R_2^3 - R_1^3}{(R_2^2 - R_1^2)^{5/4}} \tag{11}$$

Eq. (11) can be simplified to:

$$M_V = K d_0^{1/2} \upsilon_g^{-1/6} K_{IC}^{-3/4} H_V^{-1/2} \omega W^{5/4} \tag{12}$$

where K is a proportional constant.

According to Eq. (12), the material removal rate M_V will be increased with the increase of the applied static load W, the rotational speed of the tool ω, and the size of the abrasive grains d_0.

3. Experimental procedure

Experiments were performed on a drilling machine. The diamond drilling tool, which was especially designed to accept coolant (see Fig. 1), was a special diamond wheel with a external radius of $R_2 = 10$ mm and an internal radius of $R_1 = 6$ mm. Three types of diamond drilling tool were prepared, their grits being 80, 120, and 160, and their concentrations were being 100%.

A 99.5% Al_2O_3 ceramic was selected as the workpiece material and water was selected as the coolant.

The MRR is measured through a dial gauge with an accuracy of 0.001 mm. The depth of drilling per minute can be measured with a dial gauge, and then the MRR can be calculated (The MRR is the cross-sectional area of the drilling tool multiplied by the depth of drilling per minute.). The surface roughness is measured using a Talysurf 4′ (England) surface measuring instrument with a relative accuracy of 5%.

4. Experimental results and discussion

4.1. The effect of the static load

Test results show that the material removal rate tends to increase with the increase of the static load, as shown in Fig. 5, which is similar to Eq. (12).

The surface roughness is found to be slightly affected by the applied static load, increasing with the increase of the static load. The present experiments were conducted under

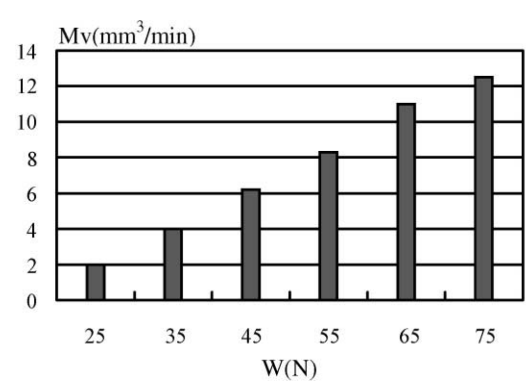

Fig. 5. The effect of the static load.

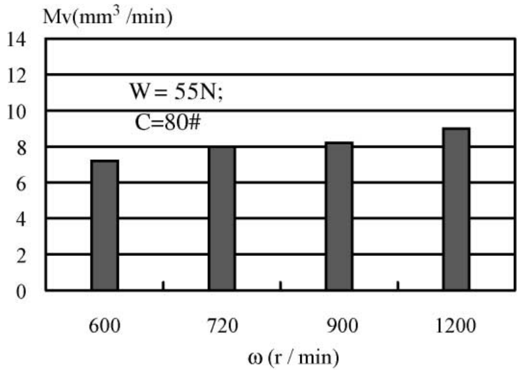

Fig. 6. The effect of the rotational speed of the drilling tool.

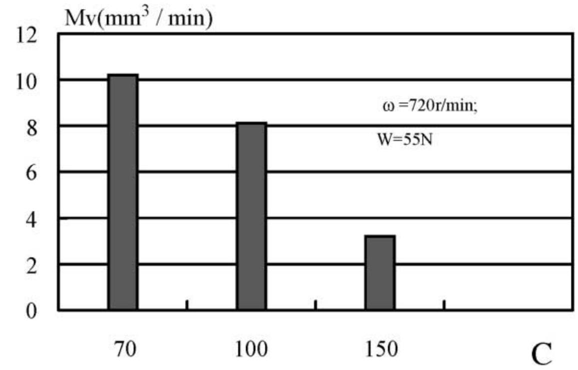

Fig. 7. The effect of grain size.

the following conditions: $\omega = 720$ rev/min, $C = 80$. When the static load W is 25, 35, 45, 55, 65 N, the surface roughness (Ra) is 0.0040, 0.0040, 0.0042, 0.0045, and 0.0045 mm, respectively.

4.2. The effect of the rotational speed of the drilling tool

Fig. 6 shows the effect of the rotational speed of the drilling tool on the MRR. An increase of the rotational speed of the drilling tool causes an increase in the MRR. As there are some other factors affecting the MRR, for example the flushing of swarf and the self-sharpening of abrasive grains, the MRR is not proportional to the rotational speed of the drilling tool.

It is very important for high material removal rate to flush away the swarf. With the increase of the rotational speed of the drilling tool, a lot of swarf is formed, and flushing it away becomes increasingly more difficult. This will also affect the self-sharpening of the abrasive grains. Generally speaking, self-sharpening of abrasive grains include two components, self-sharpening through progressive abrasive grain fragmentation and self-sharpening through progressive bond erosion. When the swarf is not completely flushed away, bond erosion and abrasive grain fragmentation become difficult, resulting in the dulling of the drilling tool: thus the MRR will be affected. Additionally, the flushing of swarf is related to the pressure of the coolant. In the present experiments, the pressure of the coolant is 2.0×10^4 Pa. Under this condition, loading occurred when the rotational speed of the drilling tool was 1200 rpm.

The surface roughness decreases with an increase of the rotational speed of the drilling tool. The present experiments were conducted under the following conditions: $W = 55$ N, $C = 80$. When the rotation speed ω is 520, 720, 900 and 1120 rev/min, the surface roughness (Ra) is 0.0055, 0.0045, 0.0042, and 0.0042 mm, respectively.

4.3. The effect of the grain size

According to Eq. (12), the material removal rate will increase with the increase of the grain size, and this is confirmed by the test results, as shown in Fig. 7.

The size of the abrasive grain can greatly affect the surface roughness. The surface roughness depends mainly on the size of the abrasive grains. The greater is the grain size, the rougher is the finished surface. The present experiments were conducted under the following conditions: $W = 55$ N, $\omega = 720$ rev/min. When the C is 80, 120, and 160, the surface roughness (Ra) is 0.0045, 0.0040, and 0.0020 mm, respectively.

5. Conclusions

The basic mechanism of the diamond tool drilling of ceramics has been studied, and the effect on the material removal rate has been explored. The test results show that any increase in terms of the static load applied, the rotational speed of the drilling tool, and the size of abrasive grains, results in an increase of the material removal rate. The relationship between the roughness of the finished surface and each parameter is given: the finished surface roughness increase with increase of the static load, decrease of the rotational speed, and increase of the abrasive grain size.

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