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Effect of grinding parameters on the reliability of alumina

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Abstract

In the present study, the effect of grinding parameters on the reliability of alumina specimens is investigated. The reliability is characterized by using the Weibull statistics. The grinding parameters investigated are the wheel depth of cut (downfeed), the table speed and the peripheral speed of wheel (wheel speed). The downfeed is varied from 10 to 30 μm per pass, the table speed from 0.17 to 0.27 m/s, the wheel speed from 20 to 33 m/s. The effect of the grinding parameters can be combined into a single parameter, the maximum grit depth of cut. The reliability shows strong dependence on the maximum grit depth of cut. The Weibull modulus can be as high as 10.9 as a low value of the maximum grit depth of cut is used. Nevertheless, the Weibull modulus is only 6.9 for the case that a high value of the maximum grit of cut is applied. © 1998 Elsevier Science S.A.

Keywords: Grinding parameters; Alumina; Reliability

1. Introduction

Alumina is superior for its hardness, its chemical stability and its availability. The potential of applying alumina as structural components is thus high. For structural applications, dimensional tolerance has to be tightly controlled. Abrasive grinding is therefore frequently applied to meet the requirement. However, the grinding of alumina ceramics is a complex process for the hardness of alumina is high and the toughness is low [1]. Considerable research activities have been focused on the process [2–6]. Previous studies indicated that the strength after grinding depends strongly on the grinding parameters [7,8]. The important grinding parameters are the wheel depth of cut (downfeed), the table speed and the peripheral speed of wheel (wheel speed). Among these parameters, the effect of downfeed on the strength after grinding has been intensively investigated [4,5,7–9]. However, the effect of table speed and wheel speed on strength attracted less attention.

The effect of grinding parameters can be combined into a single parameter, the maximum depth of cut by diamond grit, g. The definition of the maximum grit depth of cut can be seen in Fig. 1. The maximum grit depth of cut has been expressed as [10]

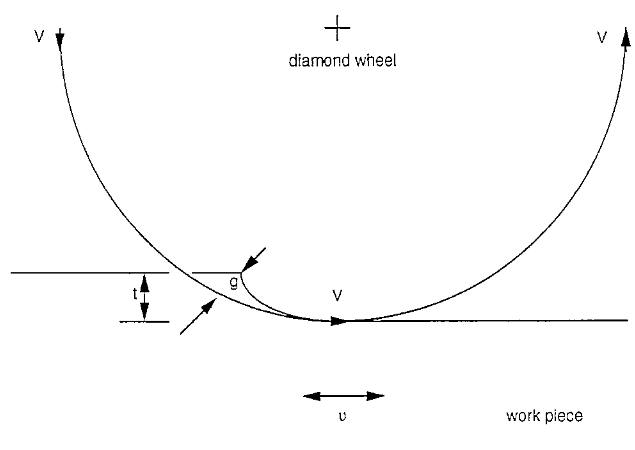

Fig. 1. Schematic diagram for the grinding process [10].

$$g=1.26\left(\frac{6F}{\pi d^3}\tan\gamma\right)^{-1/3}\left(\frac{1}{D}\right)^{1/6}t^{1/6}\left(\frac{v}{V}\right)^{1/3} \quad (1)$$

In the above equation, F is the percentage of diamond grit in the wheel, d the size of diamond grit, 2γ the vertex angle of diamond grit, D the wheel diameter, t the downfeed, v the table speed and V the wheel speed. As the value of g is high, the contact force applied by diamond grit on the work piece is high [10]. The amount and size of the subsurface flaws

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induced during grinding are increased with the contact force [7]. In the case of SiC, the strength has been reported to decrease exponentially with g [10].

For structural applications, both high strength and high reliability are desirable. However, less attention has been given to the effect of grinding parameters on the reliability. The distribution of the strength of ceramic components underlines their reliability. If the strength distribution is wide, the reliability is low. Because ceramics are brittle, the fracture of brittle ceramics is originated from a critical flaw. The distribution of strength thus corresponds to the size distribution of critical flaws. The grinding process can generate surface and subsurface flaws [2,4,5]. However, many flaws exist in the ceramic components before they are machined. Therefore, there are two types of flaws in the machined components. One type of flaw is related to the powder characteristics, forming techniques and contamination. These flaws are usually in the form of abnormal grains, large pores etc., in the fired components. Owing to the non-uniform heating, the contamination from the furnace, or the evaporation of some ingredients, flaws are frequently found near the surface [11]. This type of flaw can be termed processing flaw. The other type of flaw is formed during machining. This type of flaw can be termed machining flaw. These two types of flaws are formed in sequence. The size distribution of the processing flaws can be altered by grinding. The reliability of ceramic components thus depends on the grinding process.

The variation of strength can be characterized in terms of Weibull two-parameter statistics as

$$\ln\{\ln[1/(1-F)]\}=m \ln \sigma - m \ln \sigma_o + \text{constant} \quad (2)$$

In the above equation, σ is the strength of the specimen, σ_o the characteristic strength that corresponds to 63.2% probability of failure, and m the Weibull modulus. F is the probability of failure which is calculated using the following equation

$$F=(n-0.5)/N \quad (3)$$

In the equation, n is the nth specimen as the experimental data are ranked in order, and N the total number of specimens. In the present study, the influence of grinding parameters on the reliability of alumina is investigated. The reliability is characterized by using the Weibull statistics.

2. Experimental procedures

The alumina specimens were prepared by die-pressing an alumina powder (AL-160SG, 99.5% Al_2O_3, mean particle size = 0.5 μm, Showa Aluminum Industries, Tokyo, Japan) into rectangular bars. The pressing pressure employed was 140 MPa. Sintering was performed at 1600°C for 1 h. The size of the rectangular bars is $3.2 \times 4.0 \times 44$ mm after firing. Grinding was performed using a surface grinder with a resin bonded 325 grit diamond wheel. The diameter of the wheel is 175 mm. The wheel was first trued by grinding a low carbon steel. The wheel was then dressed with a porous alumina dressing stick. A water-based oil emulsion grinding fluid was used for cooling. The specimens were ground longitudinally. The downfeed was varied from 5 to 30 μm per pass. The table speed was varied from 0.10 to 0.27 m s^{-1}. The wheel speed was varied from 20 to 33 m s^{-1}. A constant thickness of 0.2 mm of the specimen was removed. More than 24 specimens were used for each grinding condition.

The densities of the as-sintered specimens were determined by the water displacement method. The grain boundaries were revealed by thermally etching the polished specimens. Ground surfaces were observed with scanning electron microscopy (SEM). The grain size was determined using the linear intercept technique. More than 300 grains were counted. Four-point bending technique was used to determine the flexural strength of the specimens. The upper and lower spans were 10 mm and 30 mm, respectively. The rate of loading was 0.083 mm s^{-1}. The surface roughness of the ground surfaces was measured with a stylus surface profilometer. For each grinding conditions, 15 specimens were used for roughness determination. More than three measurements were taken from each specimen.

3. Results and discussion

The average density of the as-sintered specimens was 3.91 g cm^{-3}. It corresponded to 98.2% of the theoretical density. The average size of grains was 1.9 μm. The maximum grain observed was 25 μm (Fig. 2).

The surface roughness of the specimens ground with different grinding parameters is shown in Table 1; the surface roughness of the as-sintered specimens is also shown for comparison. The surface roughness of the as-sintered specimens is significantly decreased by the grinding process. The microstructure of a typical ground surface is shown in Fig. 3. There are many pullouts on the surface. A similar morphology has also been reported by Xu et al. [4,5]. The material removing mechanism has been suggested as the grain disintegration that results from grain boundary microcracks.

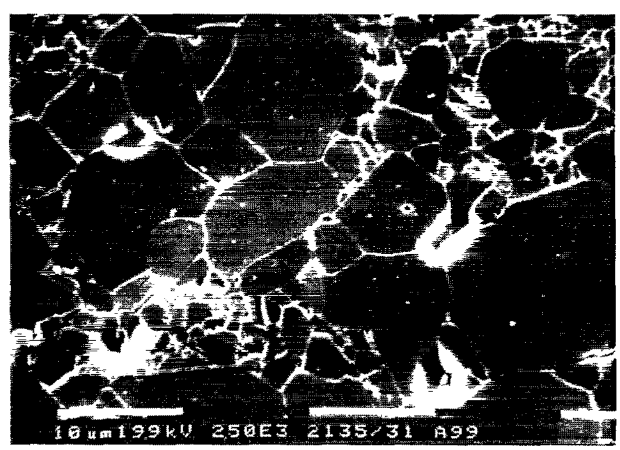

Fig. 2. The typical microstructure of the specimens.

Table 1
The surface roughness, average strength and Weibull modulus of the specimens ground with different grinding parameters

Downfeed (μm per pass)	Table speed (m s^{-1})	Wheel speed (m s^{-1})	R_a (μm)	R_{max} (μm)	Average strength (MPa)	Weibull modulus	Number of specimens
0 [a]	0.17	27.5	0.68	9.6	205	8.2	30
10	0.17	27.5	0.34	5.5	248	10.9	46
20	0.17	27.5	0.34	6.5	255	9.0	28
30	0.17	27.5	0.36	6.3	232	6.9	29
10	0.27	27.5	0.41	7.0	247	8.0	28
10	0.17	20.0	0.34	7.0	246	10.5	24
10	0.17	33.0	0.31	5.0	263	9.8	24

[a] As-sintered.

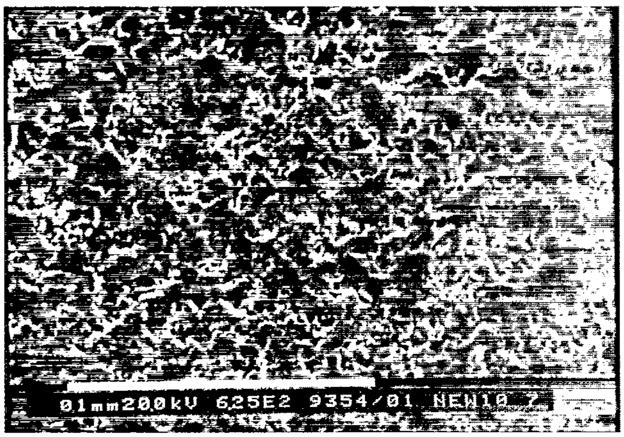

Fig. 3. A typical microstructure of the ground surface. The specimen was ground with the downfeed of 10 mm per pass, the table speed of 0.17 m s^{-1} and the wheel speed of 27.5 m s^{-1}.

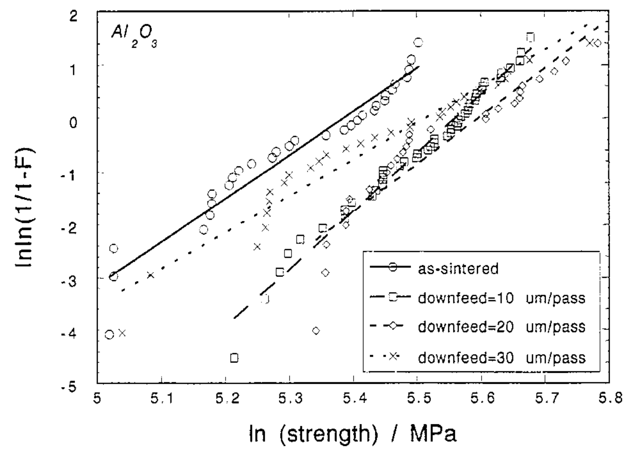

Fig. 4. The Weibull curves for the specimens ground with different downfeed. The wheel speed is 27.5 m s^{-1}, the table speed 0.17 m s^{-1}.

3.1. Effect of downfeed

The Weibull distribution for the specimens ground with different downfeed is shown in Fig. 4. The Weibull distribution for the as-sintered specimens is also shown for comparison. By using the least-square regression analysis, the value of Weibull modulus can be determined. The average strength and Weibull modulus are shown in Table 1. The scatter of the Weibull modulus can be expressed in terms of the coefficient of variation, CV, as

$$CV = (\text{standard deviation})/(\text{mean value}) \tag{4}$$

Ritter et al. [12] and Service et al. [13] had used a Monte Carlo simulation technique to estimate the values of CV. Their analysis indicated that the value of CV is decreased with the increase of the number of specimens. As 20 specimens were used, the value of CV was 0.22. The value of CV was 0.18 for 30 specimens. Ritter et al. also suggested that the 90% confidence level for 30 specimens is 2.3 and the Weibull modulus is 10 [12]. The dependence of reliability on grinding parameters can only be determined by using large amounts of specimens. The number of specimens used for each grinding condition is shown in Table 1.

From Table 1, the average strength of the as-sintered specimens is significantly increased after grinding. As the specimens are ground at the downfeed of 10 μm per pass, the table speed of 0.17 m s^{-1} and the wheel speed of 27.5 m s^{-1}, the Weibull modulus is 2.7 higher than that of as-sintered specimens. The reliability of the as-sintered specimens is thus enhanced by grinding with the grinding condition. As the downfeed is increased to 30 μm per pass, the Weibull modulus is decreased to 6.9. The Weibull modulus of 6.9 is close to 8.2; however, it is much lower than 10.9. It indicates that the reliability depends strongly on the amount of downfeed. During sintering, large flaws are easily formed near the surface [11]. The surface flaws can be removed or reduced in size by abrasive grinding. The strength is thus enhanced. Furthermore, since the distribution of critical flaw size is narrowed, the reliability is also increased. However, as the downfeed is 30 μm per pass, the contact force is high enough to induce large machining flaws. The flaw size is again broadened. The reliability is reduced. The grinding process can also induce residual stresses near the surface [11,14,15]. The presence of residual stress increases the strength after grinding. The average strength of the specimens after grinding is therefore higher than that of the as-sintered specimens (Table

1). Many flaws are formed as heavy cuts are used. The residual stresses are relaxed [11]. The average strength is then decreased as the downfeed is 30 μm per pass.

3.2. Effect of table and wheel speeds

The effect of table speed on the surface roughness, average strength and Weibull modulus of the specimens is also shown in Table 1. The Weibull distribution of the specimens is shown in Fig. 5. The surface roughness increases slightly with increasing table speed. Within the range of the table speed investigated, the average strength is independent of table speed. The Weibull modulus also shows little dependence on the table speed. It may be owing to the small range of the table speed investigated in the present study.

The effect of wheel speed on the surface roughness, average strength and Weibull modulus of the specimens is also shown in Table 1. The Weibull distribution of the specimens is shown in Fig. 6. Within the range of the wheel speed investigated, the influence of wheel speed on the surface roughness, strength and reliability is negligible.

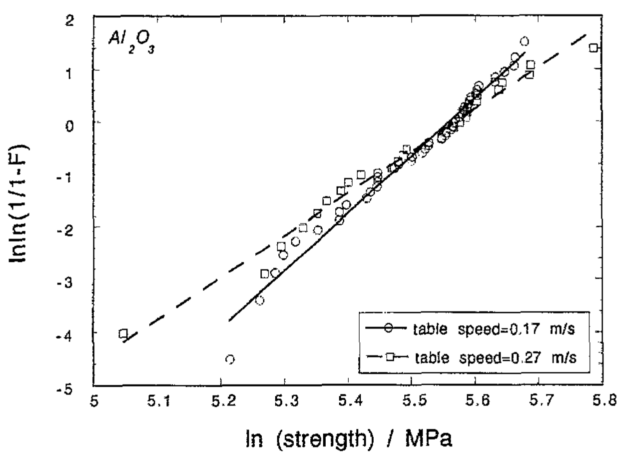

Fig. 5. The Weibull curves for the specimens ground with different table speed. The downfeed is 10 μm per pass, the wheel speed 27.5 m s^{-1}.

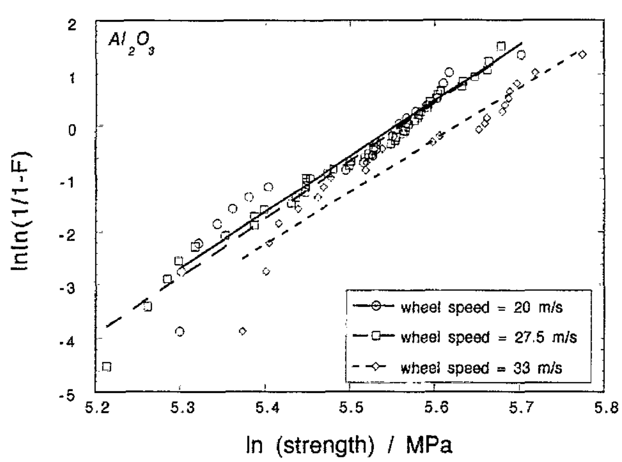

Fig. 6. The Weibull curves for the specimens ground with different wheel speed. The downfeed is 10 μm per pass, the table speed 0.17 m s^{-1}.

3.3. The combining effect of grinding parameters

The combining effect of grinding parameters can be evaluated by using the parameter of maximum grit depth of cut. The values of F, d, γ and D in Eq. (1) are assumed as constants during machining. By taking 0.5 for F, 44×10^{-6} m for d, 75 for γ [10] and 175 mm for D, the value of g can be estimated. The surface roughness is shown as a function of g in Fig. 7. As the maximum grit depth of cut is increased, the contacting force applied by the diamond grit is increased. Therefore, more grains are pulled out from the surface of work piece. The surface roughness is thus increased with the increase of g.

The average strength is shown as a function of maximum grit depth of cut in Fig. 8. Contrary to the grinding of SiC [10], the strength is decreased linearly instead of exponentially with the increase of the maximum grit depth of cut. It suggests that the alumina specimens used in this study are less sensitive to the grinding conditions.

The Weibull modulus is shown as a function of maximum grit depth of cut in Fig. 9. The contact force is increased with the increase of the maximum grit depth of cut. Higher contact force can induce larger flaws in the near surface region. The strength and Weibull modulus are thus reduced with the increase of the maximum grit depth of cut. The trend shown

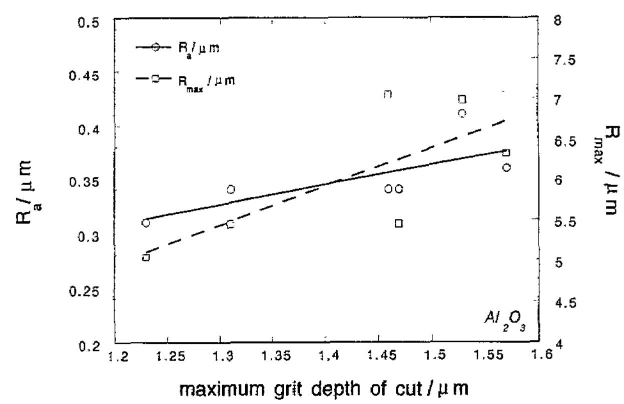

Fig. 7. The surface roughness as a function of maximum grit depth of cut.

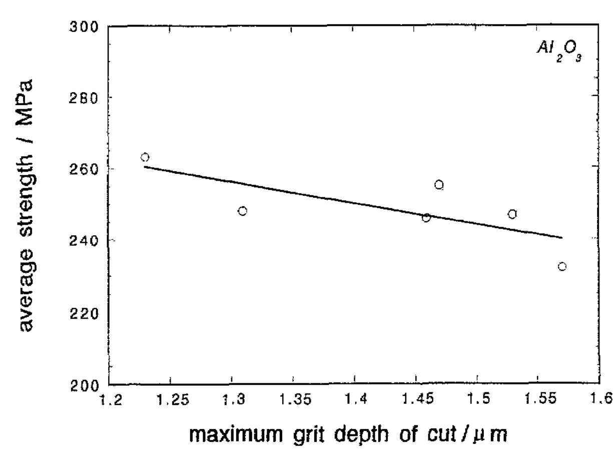

Fig. 8. The average strength as a function of maximum grit depth of cut.

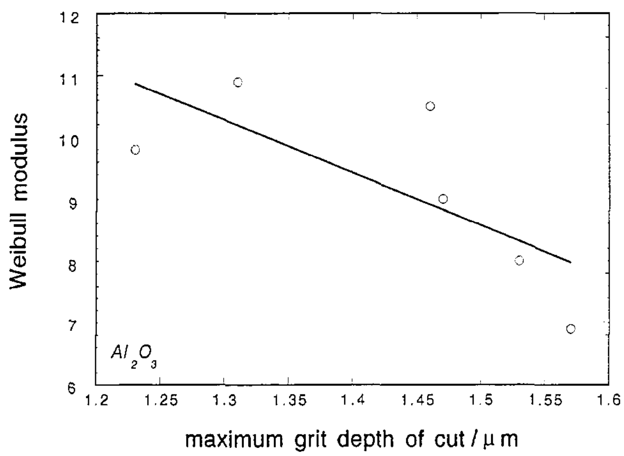

Fig. 9. The Weibull modulus as a function of maximum grit depth of cut.

in Figs. 7 and 8 and 9 is similar to one another. The figures indicate that the surface quality, strength and reliability depend strongly on grinding parameters. It also suggests that the maximum grit depth of cut is a suitable indicator for the grinding process.

4. Conclusions

The effect of the grinding parameters on the surface quality, strength and reliability of alumina is investigated. As the grinding parameters are changed, the maximum depth of cut by diamond grit is also altered. The surface roughness is increased with the increase of the maximum grit depth of cut. The strength and Weibull modulus are decreased linearly with the increase of the maximum grit depth of cut.

Acknowledgements

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