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Machinability of Heat Treated Silicon Powder Compacts

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Abstract

One major problem and limitation of processing complex-shaped ceramic components is machining. From the machining cost and ease of process points of view, reaction-bonded silicon nitride (RBSN) largely benefits from its ability to form a near-net-shape product. One way to determine the machinability of heat-treated silicon powder compact is to manifest speed/feed diagrams of lathe turn and drill operations. The turned samples were characterised by measuring surface roughness average (Ra) and the drilled samples were characterised by measuring chipping edge area. These two measurements when plotted against a factor called material removal rate / rotational speed (MRR/V) were considered sufficient to indicate machinability of the powder compacts.

Keywords : Machining, Machinability, Powder compact.

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Introduction

By reaction with nitrogen, a very loosely packed silicon powder formed a coherent monolithic silicon nitride replica of the original shape of appreciable strength (Popper and Ruddelsden, 1961). The reaction is accompanied by a 22% volume expansion that occurs in void space of the powder compact. In other words, this is a near-net-shape process that lends itself to the formation of complex shapes without shrinkage and expensive machining (Riley, 2000). Consequently an insight into machinability of heat-treated silicon powder compact is of primary significance.

Studies on machinability of ceramics have been concentrated on each stage; i.e. green compact or sintered products. The studies on green compact (Song, *et al.* 1997; and Besshi, *et al.* 1999) related initial defect size to handleablility and resistance to clamping and chipping damage. While researchers (Baik, *et al.* 1997; Boccaccini, 1997; Hockin, *et al.* 1995) tend to relate machinability of sintered surfaces with factors relating to hardness and toughness of the samples. However, the aim of this study focused between the two extremes; i.e the machinability of pre-sintered compacts.

A few parameters; i.e. material removal rate (MRR) together with feed and speed of machining operation, were utilized and correlated with finished surface characteristics. The MRR has been defined as the uncut area multiplied by the rate at which the tool is moved perpendicular to the uncut area (Cohen, 1996). For turning operation, the area removed is an annular ring of outside diameter D and inside diameter D_1 Figure 1. The uncut area is $\pi(D^2-D_1^2)/4$. The specimen was rotated at N revolutions per minute, while the tool was fed at f_r units (millimeters per revolution)

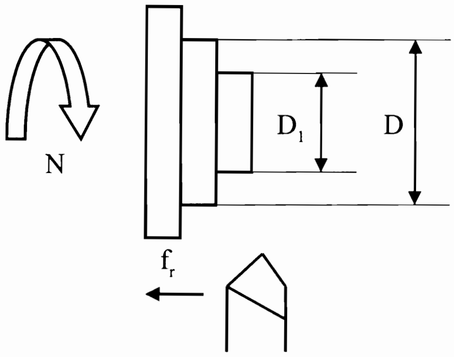


Figure 1 Schematic of specimen during turning operation

Therefore, the material removal rate is:

$$MRR = \frac{\pi(D^2 - D_1^2)}{4} \cdot f_r \cdot N \qquad (1)$$

For drilling, a drill of diameter D is rotated at N revolutions per minute and fed at f_r (unit distance per revolution). The uncut area is the area covered by the drill, or $\pi D^2/4$, while the feed rate perpendicular to the area is f_r N. Therefore, the material removal rate for drilling is :

$$MRR = \pi D^2/4 \cdot f_r \cdot N \qquad (2)$$

The cutting speeds (m/min) can be converted to rotational speed as follows:

$$V = \pi DN \qquad (3)$$

These machining parameters; namely speed, feed and MRR/V were correlated with surface roughness average (Ra) of turned surface and edge chipping area of drilled surface.

Experiment Procedure

Silicon metal with average size of 25 microns was selected in this experiment. Table 1 shows the chemical composition of silicon metal. The silicon powder mixed with 2 wt% polyvinyl alcohol (PVA) binder was compacted into a cylindrical shape of 50 mm diameter and 17.5 mm height. The green compact was heated at 150°C/hr to 500°C then heated at 200°C/hr to 1200°C and held for 10 hrs in argon.

The machining was performed on a Plant-Sliven CU 500M lathe using a high-speed steel cutting tool. The spindle speed and feed rate were varied in the range of 250, 315, 400, and 500 rpm and 7.41, 8.55, 10.10, 12.35, and 14.82 mm/min, respectively. The top surface of a sample was turned to provide a reference plane for accurate measure of depth of cut. Steps were then turned at the designed feed and speed with a 2 mm depth of cut as shown in Figure 1. The surface roughness average (Ra) of turned surface was measured by using a surface profiler Dektak (Birkby and Dransfield, 1994) ST (Veeco) and a Mitutoyo surftest 201.

The perforation was performed on an ERLO (SIEMENS) machine using a 3 mm diameter hardened steel bit. The drilling conditions consisted of a cutting speed of 288, 480, 685 and 1150 rpm and a feed rate of 0.08, 0.16, 0.24 and 0.35 m/min. The chipping edge areas were measured using an Olympus optical microscope connected with an image analysis Omnimet 4 program.

Table 1 Chemical composition of silicon metal

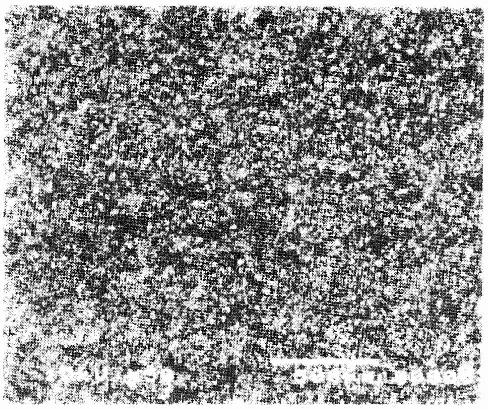
Siliconmetal	Element (% by wt.)				
	Si	Al	Ca	Fe	W
	99.11	0.14	0.47	0.17	0.10

Results and discussion

Observation of the machined surface by naked eyes revealed that a high speed, low cutting tool feed rate was preferable for a fine smooth surface. Figure 2 compares typical 'smooth' and 'rippled' surfaces of the turned samples. It can be seen that the feature on the 'smooth' surface was dominated by inter-agglomerate fracture. While the failure on the 'rippled' surface which consisted of smooth part and an uneven part was exacerbated by crack propagation and linking among inter-agglomerate flaws at a high feed rate.

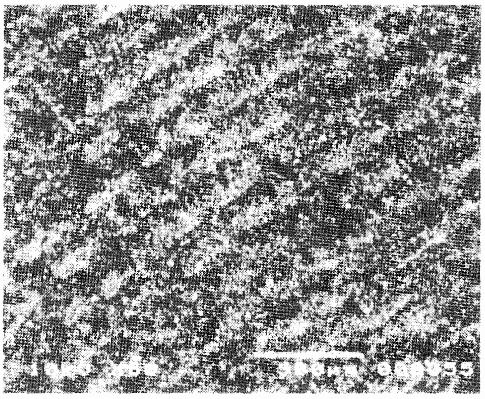
The dependence of surface roughness average (Ra) on feed rate and speed varied from approximately 3 to 6 microns as seen in (Figure 3). The surface roughness average seemed to be more sensitive to speed than feed rate. Nevertheless, it should be noted that the Ra of 3.5 microns was rather favourable when compared with the Ra of green alumina compact of 7.1 microns, measured under the best cutting conditions (Sentoku, *et al.* 1996).

(a)



500 rpm, 7.41 mm/min

(b)



250 rpm, 12.35 mm/min

Figure 2 SEM image of typical (a) 'smooth' and (b) 'rippled' surfaces.

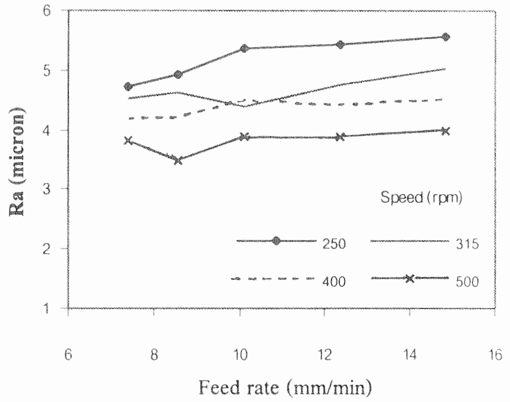
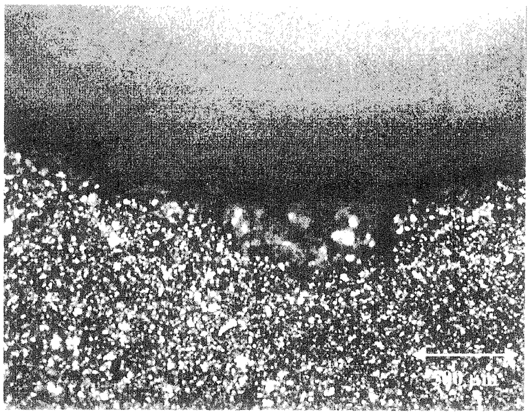


Figure 3 Speed/feed diagram of silicon compact of turning operation

Observations of samples drilled at various feed and speed under an optical microscope (Figure 4) exhibit small edge chipping. A plot of measured chipping edge area in drilling against MRR/V indicates linear correlation, similar to that of Ra in turning against MRR/V Figure 5. The slope of the plots suggest that drilling is far more sensitive to the factor MRR/V than turning operation. This is obviously caused by stress concentration at edge. The x-intercept in drilling operation provides a sufficient guideline for an appropriate material removal rate.



685 rpm, 0.08 m/min

Figure 4 Optical microscope image of drilled surface

The lower case mechanism of the material removal for both turning and drilling operations could be explained by Griffith's theory of unstable crack propagation and by the weakest link theory of Weibull. Elastic strain energy is stored in front of the cutting tip before propagation occurs. Once cracks start to propagate they tend to travel further to dissipate stored energy before linking to form a chip. Inter-agglomerate boundaries provide suitable interlinking defects.

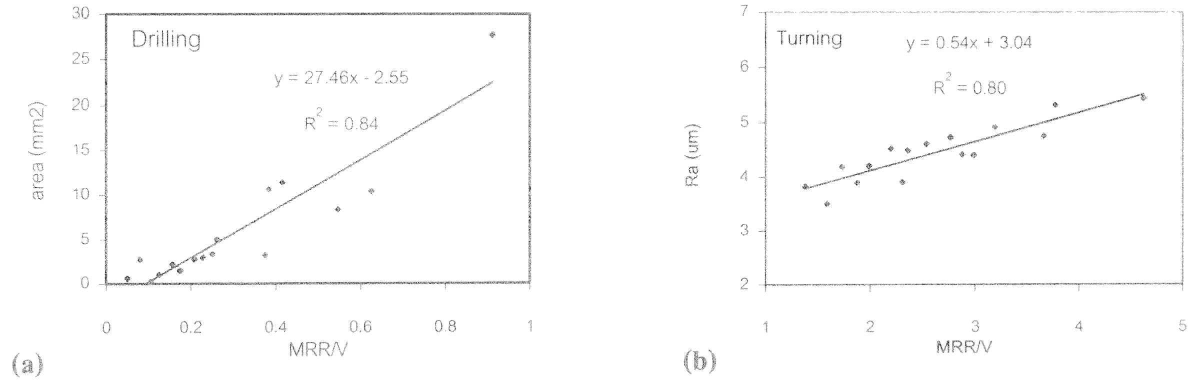


Figure 5 (a) The plot of measured-chipping edge area in drilling against MRR/V

(b) The plot of Ra in turning againt MRR/V

Conclusions

Pre-sintered silicon powder compact can be machined by turning and drilling operations. At high-speed, a low cutting tool feed rate was preferable for a fine smooth surface and a small edge chipping area. Drilling operation was more sensitive to the factor MRR/V than the turning factor because of stress concentration at the edge. The x–intercept indicates that the drilling factor (MRR/V) should be less than 0.2 for an acceptable drilled hole, while the factor MRR/V was less influential in turning operation.

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