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Crack-free ductile mode grinding of fused silica under controllable dry grinding conditions

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ABSTRACT

A crack-free ductile mode grinding of fused silica was realized by a controllable dry grinding process in this research, which is attributed to the improvement of fused silica's ductile machinability induced by the high grinding temperature. The plastic deformation of fused silica consists of shear flow and densification. Plastic deformation mechanisms and cracking behaviors related to densification were investigated firstly by high temperature nanoindentation experiments to reveal the ductile–brittle transition mechanisms. Fused silica exhibits less densification and more shear flow at high temperature than room temperature. The critical ductile–brittle transition load of fused silica is higher at high temperature than room temperature. These results may lead to the improvement of the fused silica's ductile machinability at high temperature. Dry grinding experiments were conducted to investigate the effect of grinding depth. A mathematical model is established to predict the maximum temperature in workpiece. A novel infrared radiation (IR) transmission on-line measurement method was presented to acquire the workpiece temperature in the contact zone directly. The predicted results coincide well with the experiment results. Contrary to the conventional experience, a large grinding depth is beneficial for the surface quality and integrity in the dry grinding of fused silica due to the increased grinding temperature; however, the excessive grinding depth results in grinding wheel burn. The ductile grinding depth of the fused silica increases from sub-micrometers to 5 μm by dry grinding which makes the grinding process more controllable and effective.

1. Introduction

Amorphous silicon dioxide, i.e., fused silica, is an excellent lens and window material for ultraviolet laser transmission in photolithographic applications, high-peak-power laser fusion facilities and space telescopes for its high ultraviolet transmission, low expansion coefficient and high laser damage threshold [1]. Currently, fused silica lenses are finished by grinding, lapping and polishing. The polishing process costs over 60% of the entire production cycle [2]; thus, it is important to produce higher surface integrity in the grinding process to reduce the polishing time and the cost of production.

Ductile mode grinding of hard and brittle materials is an attractive method for efficiently generating a surface with nanometer or sub-nanometer level surface roughness. It is widely recognized hard and brittle materials could be machined in ductile mode if the undeformed chip thickness were controlled to be small enough [3].

Single-crystal silica, ceramics and most optical glass are reported to be grindable in ductile mode with a grinding depth of several micrometers using precision machine tools [4–6]. However, it is extremely difficult to grind fused silica in ductile mode without causing any cracks. Taper grinding experiments on fused silica surfaces without damage demonstrated that critical grinding depth of the ductile–brittle transition was 0.2 μm [7]. The extremely narrow range of critical depth makes the crack-free ductile mode grinding of fused silica uncontrollable and inefficient. Many efforts for ductile grinding of fused silica, including electrolytic in-process dressing(ELID) [8], using ultra-fine grits wheels [9] or truncation coarse grain wheels [10], succeed to reduce the roughness and sub-surface damage (SSD) depth of fused silica, while failed to produce an ultra-smooth fused silica surface

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Nomenclature

d_c	critical chip thickness
E	Young's modulus
H	hardness
K_c	fracture toughness
v_s	wheel speed
v_w	workpiece feed rate
Δ	grinding depth
g_m	undeformed chip thickness
R_D	section area ratio of sink-in to indenter
S_a	actual section area of indentation
S_i	the calculated section area of the indenter
$\bar{q}$	average heat power density
b	width of the grinding wheel
c	specific heat
D	diameter of grinding wheel
θ	temperature rise
l	geometrical wheel workpiece contact length
ε	ratio of heat power into the workpiece
λ	thermal conductivity
ρ	density
F_0	tangential grinding force per unit equivalent grinding thickness
a_{ep}	equivalent grinding thickness

without any surface and sub-surface cracks in controllable conditions.

Brittle–ductile transition in machining of hard brittle materials is a complex interaction of tool (grain) geometry, processing parameters, environmental conditions (temperature and humidity), material properties, et al. [11]. The factors affecting the transition are generally divided into two types: external factors, such as stress condition and strain rate et al., and internal factors, such as material properties. Actually tool (grain) geometry, processing parameters et al. affect the brittle–ductile transition through the variation of stress condition and strain rate while the environmental conditions affect through changing the intrinsic material properties.

Without considering the external factors, Bifano presented a model indicating the relationship between the critical ductile–brittle transition chip thickness d_c and intrinsic material properties Young's modulus E, hardness H and the fracture toughness K_c [9]:

$$d_c \propto \left(\frac{E}{H}\right)\left(\frac{K_c}{H}\right)^2 \tag{1}$$

The E, H and K_c of fused silica are 72 GPa, 7.3 GPa, 1.3 MPa $m^{1/2}$, respectively [12]. For comparation, the E, H and K_c of soda-lime-silica glass are 70 GPa, 5.7 GPa, 0.6 MPa $m^{1/2}$, respectively [13]. According to Eq. (1) the calculated d_c of fused silica is much larger than that of soda-lime-silica glass. Nevertheless, the ductile machining of fused silica is actually much more difficult than soda-lime-silica.

Hardness is the plastic deformation resistance of material. However, it does not shed light on the mechanism of permanent deformation of glass under stress, which can be primarily divided into two modes: volume-conservative plastic (or shear) flow and volume contraction densification [14]. Fused silica is called anomalous glass [15] due to its predominant densification under stress. In ductile mode grinding, the material is removed by shear flow while densification has no contribution to chip removal. Thus hardness in Eq. (1) cannot characterize the glasses' ductile machinability.

The fracture toughness, which is also called fracture resistance is calculated by the following equation:

$$K_C = \left(\frac{E}{H}\right)^{0.5}\left(\frac{P}{c}\right)^{1.5} \tag{2}$$

where c is the lengths of radial cracks in indentation.

Densification causes fused silica to act differently in cracking behaviors compared to normal glass [16]. It tends to initiate cone cracks around the impression while the normal glass trend to initiate radial cracks. The radial cracks' lengths of fused silica are always shorter than that of a normal glass [17]. Nevertheless, it is more difficult to grind fused silica in ductile mode on contrary. Thus toughness in Eq. (1) cannot characterize the glasses' fracture resistance. It has been concluded that the plastic deformation and cracking behaviors of glass have a strong relationship with densification [18–20].

Michel et al. [12] experimentally investigated the effects of temperature on hardness and crack nucleation of fused silica during Vickers indentation under the loads of 5 N and 40 N. Comparing with room temperature, the radial crack length and the threshold for the cone cracks of fused silica increase at high temperature. Shear flow is responsible for the residual stress due to the elastic/plastic mismatch [21] whereas densification is not. The radial cracks propagate during the unloading process due to the residual stress induced by shear flow. We can infer that high temperature may improve the ductile machinability of fused silica for its more shear flow based on Michel's study. However, deformation mechanisms and cracking behaviors under nanoindentation below 500 mN which more closely approximates to the load on a single grain in the actual grinding process need further investigation.

This paper presents a dry grinding process using a vitrified bond CBN grinding wheel with high temperature resistance to achieve crack-free ductile mode grinding of fused silica. The high temperature induced by grinding heat improves the ductile machinability of fused silica. Instead of an extremely narrow chip thickness for ductile grinding with coolant, a large grinding depth makes the proposed process more controllable and effective. The physical and chemical properties of fused silica are stable at high temperatures. The annealing point of it is 1200 °C while the softening point is 1600 °C. It cannot be oxidized at high temperatures; thus, the grinding burn of fused silica will not occur at extremely high grinding temperatures during dry grinding. Plastic deformation mechanisms and cracking behaviors related to the densification are investigated firstly by high temperature nanoindentation experiments below 500 mN to reveal the ductile–brittle transition mechanisms. Dry grinding experiments are conducted to investigate the effect of grinding depth for its significance of processing efficiency. A mathematical model is established to predict the maximum temperature at grinding zone. A novel infrared radiation (IR) transmission on-line measurement method was presented to acquire the workpiece temperature in the contact zone directly during surface grinding process.

2. Experiments

The specimens are high purity synthetic fused silica with a transmission wavelength of 0.175–2.5 μm. This type of fused silica is particularly developed for ultraviolet laser transmission. The size of the specimens is $\phi 20$ mm × 1.5 mm.