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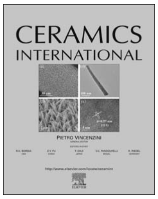

Controlled material removal mode and depth of micro cracks in precision grinding of fused silica – A theoretical model and experimental verification

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ABSTRACT

A critical function for crack propagation for the single grit scratching of fused silica is developed based on the fracture mechanics. The effects of original crack density on the surface, strain rate and grinding coolant are considered in the function. A theoretical model for controlled material removal mode and depth of micro cracks precision grinding is presented based on the critical function for crack propagation. It can be predicted by the model that the material removal mode in the grinding of fused silica with original cracks damage will change from a ductile mode to a semi-brittle mode, a full-brittle mode and a semi-brittle mode in sequence with the increasing single grit scratching depth. It was found that the micro crack damage depth of fused silica does not increase with the single grit scratching depth after a full brittle mode grinding and it is always smaller than that after a semi brittle mode grinding even with a smaller single grit scratching depth. These interesting results are explained by the fracture mechanics. The ductile mode grinding is a recognized desirable process of fabricating fused silica while the full-brittle grinding is also a feasible process for its shallow subsurface damage, high efficiency, low grinding force and energy consumption. Therefore, the depth of micro cracks after grinding can be controlled by choosing suitable grinding parameters. Grinding experiments are conducted on fused silica. The undeformed chip thickness of randomly distributed effective grits is simulated based on 3D reconstruction of wheel topography to reveal the relationship between the grinding parameters and the single grit scratching depth. Ground surface roughness, sub-surface damage (SSD) depth and grinding force are measured and discussed. It is shown that the model predictions correlate well with the experimental trend of grinding modes.

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]. However, it is difficult to be fabricated for its high hardness and brittleness. Precision grinding is an attractive method for manufacturing fused silica lenses efficiently [2]. Generally, the material removal mechanism of fused silica in grinding process can be classified into two modes, brittle and ductile [3].

The whole fabricate process of fused silica lenses includes rough machining, semi-finishing grinding, ultra-precision grinding, lapping and polishing [4]. The ductile mode grinding is a desired process to generate a crack free surface. However, it is must be conducted in a semi-finished product with micro crack damage after the brittle semi-finishing grinding. Many efforts for ductile grinding of fused silica, including electrolytic in-process dressing(ELID) [5], using ultra-fine grits wheels [6] or truncation coarse grain wheels [7], succeed to reduce the roughness and sub-surface damage (SSD) depth of fused silica, while failed to produce an ultra-smooth fused silica surface without any surface and sub-surface cracks in controllable conditions. Brittle grinding is also an essential process for its high efficient [8]. If the depth of micro cracks can decreased in semi-finishing grinding process, the processing time for subsequent ultra-precision grinding and polishing can be reduced [9].

The brittle -ductile transition (BDT) mechanism of hard brittle materials have been investigated by continuum mechanics. The mechanic response of materials can be classified into three modes, elastic deformation, plastic deformation and fracture. The elastic deformation

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Nomenclature

F_n	normal load of single grit during a scratching process	P	probability of material fracture failure
F_t	tangential load of single grit during a scratching process	${K_{IC}}^{CR}$	correction fracture toughness for the surface with micro cracks
a	radius of plastic yielding core	${K_{IC}}^{SR}$	correction fracture toughness with high strain rate
d	scratching depth	${K_{IC}}^{WA}$	correction fracture toughness with grinding coolant
c	length of the crack beyond the plastic core	m	crack density correction fracture toughness index
φ	angle between the normal force and crack direction	$\dot{\varepsilon}$	strain rate
ψ	half cone angle of grit	p	strain rate correction fracture toughness index
σ_m	maximum stress	κ	correction coefficient of fracture toughness with grinding coolant
Π	stress coefficient	h	damage depth
K_I	stress intensity factor on the crack tip	h'	damage depth after scratching
b	effective elastic stress field width	ρ	density of diamond grits
η	effective elastic stress field width coefficient	ω	average diameter of grits
E	elastic modulus	C	grit concentration
H	hardness	M	number of grits
K_{IC}	fracture toughness	G_j	cutting edge of grit
N	surface micro cracks density	F_N	normal grinding force

is a process of storing energy. When the elastic energy stored in material is arrived the maximum limitation, the plastic deformation and fracture will occur to consume the redundant elastic energy. If the stress state satisfies the yield criteria, plastic deformation happens [10]. The flaws/defects will propagate if the elastic energy release rate is more than the specific surface energy [11]. It is believed that even for hard and brittle material more or less plastic deformation must occur before crack propagating. Based on this theory, hard brittle material can be machined in the ductile mode without crack propagation if the undeformed chip thickness is small enough [6]. If the undeformed chip thickness is larger than a critical value, plastic deformation and crack propagation may happen in the same time to induce material removal, e.g. material is machined in the brittle mode. However, few previous investigations have considered the effect of the plastic deformation on the balanced crack length and the machining force, or to use the theory to control the damage depth in hard material machining or grinding.

The BDT of hard brittle materials is a complex interaction of grits geometry, processing parameters, environmental conditions (temperature and chemical corrosion), original surface integrity, material properties, et al. [12]. The factors affecting the transition are generally divided into two types: external factors which refer to stress condition and strain rate, and internal factors which refer to material properties. Actually, grits geometry, processing parameters, original surface integrity 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. The generation of a ground surface is a complex process involving cutting by randomly distributed multiple grits (grinding wheel topography) [13,14] with high wheel speed (high strain rate) [15] in brittle rough machining surface (subsurface damaged original surface) [5] using grinding coolant (chemical corrosive to fused silica) [16]. The effect of factors summarized in above brackets on critical models for BDT is with absence of qualitied theory and needs to be researched more deeply.

In this paper, a critical function for crack propagation during single grit scratching fused silica is developed based on the fracture mechanics. The effects of crack density on the surface after rough brittle machining, strain rate and grinding coolant are considered in the function. A theoretical model for controlled material removal mode and the depth of micro cracks in precision grinding is presented based on the critical function for crack propagation to reveal the effect of the plastic deformation on single grit scratching force and microcrack damage depth. Grinding experiments are conducted on fused silica. The undeformed chip thickness of randomly distributed effective grits is simulated based on 3D reconstruction of wheel topography to reveal the relationship between grinding parameters and single grit scratching depth. Ground surface roughness, sub-surface damage (SSD) depth grinding force are discussed.

2. Theoretical model for controlled material removal mode and depth of micro cracks

Grinding surface generation is a complex process involving scratching by randomly distributed multiple grits. In order to simplify the grit-workpiece interaction during the grinding process, the single grit scratching process was analyzed firstly. As shown in Fig. 1, when a

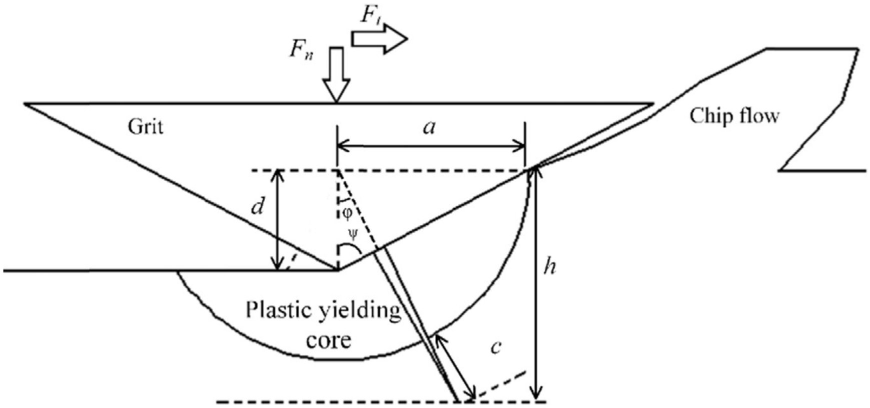

Fig. 1. Schematic of single grit scratching process.