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Vibration-assisted dry polishing of fused silica using a fixed-abrasive polisher

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ABSTRACT

Glass is a ubiquitous but essential material in everyday life and industry. The most common method for polishing glass involves the use of free abrasives. However, this method is basically non-deterministic and lacks efficiency. Therefore, vibration has been employed to aid fixed-abrasive polishing in our research. It is found that the vibration can increase the material removal rate while maintain surface quality in fixed abrasive polishing. Normalized Preston coefficients that are the index of the polishing capability of a certain polishing process considerably increase in vibration-assisted polishing process. A mathematic model is set up to interpret the increase in material removal rate for vibration process. The modeled results show that the vibration can improve material removal by increasing vibration amplitude in vertical direction while the horizontal vibration contributes little to increasing material removal rate, which agrees well with experimental results. Aside from material removal, surface morphology of polished glass was also modeled for both vibration and conventional processes. Both experimented and simulated morphology evidence that the vibration some periodic structure on polished surface. The possible mechanism in dry fixed abrasive polishing was also chemically analyzed and a probable mechanism is put forward to clarify the material removal in dry fixed abrasive polishing.

1. Introduction

Fused silica glass has a wide spectrum of scientific and industrial applications in numerous fields credited to its excellent physical and chemical properties, which endow fused silica with extensive use for lens material and photomask substrates in lithography systems, chips shields, lens and phase plates in giant lasers, etc. These systems, in general, impose stringent requirements on components. These numerous optical components were usually finished with conventional loose/free abrasive polishing followed by surface form figuring as necessary. However, material removal rate (MRR) in conventional pitch polishing is inadequate for fast polishing ground components to specular surface; typical material removal rate is 1–3 μm/h for fused silica and ~10 μm/h for BK7, respectively, in pad polishing [1–3]. Li et al. have also shown that small depressions, under occasional situations, appear on polished surface [4]. In spite of low MRR as compared to grinding, polishing process is absolutely essential in removing micro-cracks remaining in the outermost surface of ground glass due to different mechanisms of polishing from grinding process, which is referred to as subsurface damage reviewed by Wang et al. [5]. Material is removed plastically/elastically in the polishing of hard-brittle glass rather than brittle fracture regime in traditional grinding. In order to improve productivity, the MRR of polishing should be increased or alternatively the cracked layer be suppressed. Thus a number of innovative manufacturing techniques have been flourishing from the viewpoint of either enhancing the MRR of polishing or decreasing the thickness of cracked layer, representative of which are creative polishing methods and ductile grinding [6–8].

Although it is still extensively utilized in practice on workshops, conventional loose abrasive polishing is associated with insurmountable problems, e.g. lack of determinism, low efficiency, mere utilization of abrasives in slurry and environmental issues. The material removal rate in loose abrasive polishing is affected by a myriad of factors, including pad nature, abrasive concentration in slurry, and size distribution of abrasives, which, to some extent, renders loose abrasive process unpredictable. In addition to the above difficulties, the "active" abrasives is evidenced to account for merely $<0.5\%$ of abrasives over working zone [9], indicating that profuse abrasives are actually squandered. Hence some institutes and organizations [10,11] have turned to fixed abrasive polishing and they show that glass can be smoothly polished to surface roughness of 1 nm with special fixed-abrasive polishers. Fixed abrasive polishers will be instrumental in automatizing polishing process and facilitating predictable manufacture. The roadmap is

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Nomenclature

$c_L c_B$	vibrational factors in longitudinal and bending directions, respectively
$d_g d_{g\ \max} d_{g\ \min}$	size, minimum size, maximum size of abrasives
$\overline{d}_g$	mean size of abrasives
f	ultrasonic frequency
k	Preston coefficient
h_0	indentation depth of abrasive i without vibration
p	distribution density function of abrasives
r	distance of pellet center from the center of workpiece
s_i	sliding distance of abrasive i without vibration
s_{iUV}	sliding distance of abrasive i with vibration
t	time
v	relative velocity
$x_{i1} y_{i1} z_{i1}$	coordinate of abrasive i without vibration in $X_1 O_1 Y_1$
$x_{i1UV} y_{i1UV} z_{i1UV}$	coordinate of abrasive i with vibration in $X_1 O_1 Y_1$
$x_{i3UV} y_{i3UV} z_{i1UV}$	coordinate of abrasive i with vibration in $X_3 O_3 Y_3$
x_{UV}	PZT vibration in X-direction
z_{UV}	PZT vibration in Z-direction
A_i	indentation cross-sectional area of abrasive i without vibration
A_{iUV}	indentation cross-sectional area of abrasive i with vibration
A_{xUV}	vibration amplitude in X-direction
A_{zUV}	vibration amplitude in Z-direction
B	lateral/bending vibration
B_{hkl}	full-width at half maximum of diffraction peaks
C_1	coefficient of abrasive distribution density
D_{hkl}	mean crystallite size
K	constant for Scherrer formula
L	longitudinal vibration
N	the number of abrasives participating in material removal on the pellet surface
P	polishing pressure
R_a	arithmetic surface roughness
V	input voltage
δ	material removal
δ_i	material removal by abrasive i without vibration
δ_{iUV}	material removal by abrasive i with vibration
θ	Bragg angle
λ	wavelength of X-ray
σ_g	standard deviation of abrasive size
φ	phase difference
ω	workpiece rotation

followed as well and another form of fixed abrasive polisher was developed recently and the effectiveness has been revealed [12,13].

The application of ultrasonic vibration to manufacturing hard-brittle materials dates back to as long ago as 1920s, which was proposed for the purpose of fulfilling ever-increasing needs for machining difficult-to-machine materials productively[14]. The energized abrasives in fluids via an ultrasonic vibrator impinge the surface of workpiece, resulting in the removal of material, which is termed stationary ultrasonic machining prevailing in earlier applications. Afterwards, other types named rotary ultrasonic machining and cutting were implemented by Pei [15] and Moriwaki [16], respectively. Ultrasonic vibration has also been successfully integrated into chemical mechanical polishing (CMP) process to polish metals [17]. Inspired by the fact that machining performance can be ameliorated on the introduction of ultrasonic vibration into grinding/cutting processes, Li et al. [18] combines ultrasonic vibration with the fixed abrasive polisher to polish glass and preliminary results show that material removal rate can be increased by using ultrasonic vibration. This article is devoted to the understanding of the increment of material removal rate in ultrasonic vibration process and potential mechanism in fixed-abrasive polishing. A mathematical model is developed based on the indentation volume of abrasives into glass surface. The model shows that the material removal rate increase is contributed to the vertical vibration while horizontal vibration can hardly influence the material removal rate. The chemical analysis show that the material removal in dry-fixed abrasive polishing is attributed to the formation of Si–O–Ce bond.

2. Experimental

2.1. The vibration of PZT vibrator

The effectiveness of the designed PZT vibrator was first appraised with two laser vibro-meters (Ono Sokki LV-1610, Japan) and design of the PZT vibrator is detailed in [18]. The layout of the testing apparatus is illustrated in Fig. 1. The vibration amplitude correlates roughly linearly to input voltages manifested by experiments (Fig. 2).

The relation of amplitudes of longitudinal (L_1) and bending (B_1) with input V_1 is formulated

$$L_1 = c_{L1} V_1 \cos(2\pi f t) \tag{1a}$$

$$B_1 = -c_{B1} V_1 \cos(2\pi f t) \tag{1b}$$

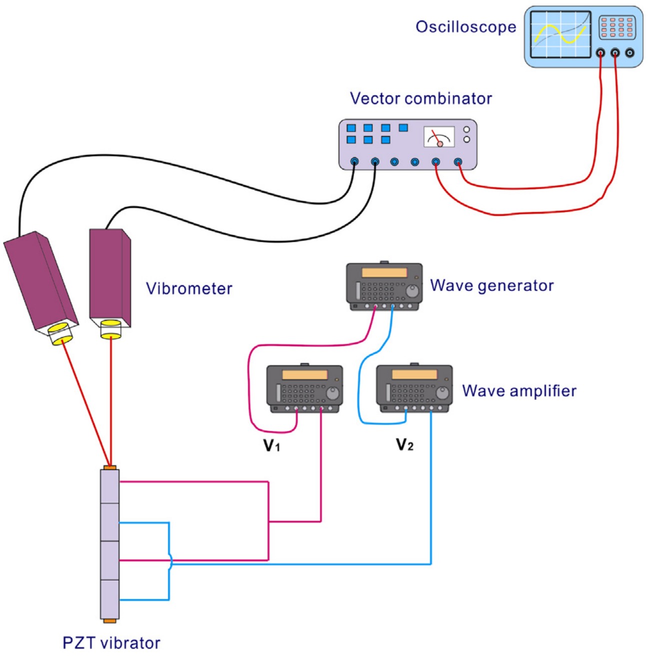

Fig. 1. Testing vibration of PZT vibrator. Two vibro-meters form an angle less than 20°. Input voltages are actually identical.