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Effects of pressure and shear stress on material removal rate in ultra-fine polishing of optical glass with magnetic compound fluid slurry

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ABSTRACT

Optical glasses used in a range of industrially important optoelectronic devices must be polished to nano-level roughness for proper device operation. Polishing process with magnetic compound fluid slurry (MCF polishing) under a rotary magnetic field is an influential candidate for the method to precisely polish optical glass. MCF slurry has been successfully utilized to polish a variety of materials, ranging from soft optical polymers to hard optical glasses. MCF was developed by mixing a magnetic fluid and a magnetorheological fluid with the same base solvent, and hence includes not only μm-sized iron particles but also nm-sized magnetite particles. To elucidate the behaviour of material removal in MCF polishing, this study measured the normal and shear forces generated in the polishing zone during polishing. From these measurements, the distributions of pressure P and shear stress τ were obtained. The distribution of material removal rate (*MRR*) was investigated through spot polishing of borosilicate glass. The effects of three process parameters, namely magnet revolution speed, MCF carrier rotational speed and working gap, on pressure P, shear stress τ and the *MRR* were also investigated. The results revealed that P is higher near the centre of the interacting area (i.e. the polishing spot centre) and the point of maximum shear stress τ appears at about 5 mm from the polishing spot centre. All of P, τ and *MRR* are sensitive to MCF carrier rotational speed and working gap but insensitive to magnet revolution speed. Shear stress is more sensitive to these process parameters than the pressure. Cross-sectional profiles of the polishing spots exhibit a characteristic symmetric W-shape; material removals are minimal at the spot centre and maximal at approximately 8.2–10.2 mm from the spot centre depending on the process parameters. *MRR* is proportional to the MCF carrier rotational speed and is negatively correlated with working gap. An *MRR* model involving both the pressure and shear stress in MCF polishing is proposed. In the model, *MRR* is more dominated by shear stress than by pressure.

1. Introduction

Optoelectronic devices such as photodiodes, photoresistors and light-emitting diodes, have been extensively used in the detection and control of radiation, including visible light, gamma rays, X-rays, ultraviolet and infrared. The usual construction material is optical glass. To meet the required performance, the surfaces of these devices must be finished to nano-level roughness with no sub-surface damage. Therefore, during the manufacturing of optoelectronic devices, the construction material is generally subjected to nano-precision polishing as the final process after machining (e.g. cutting and grinding). Nano-precision polishing not only reduces the surface roughness but also eliminates breaks, cracks and damaged layers on the work surface caused by previous processes such as ultra-fine grinding.

Conventionally, nano-precision polishing is accomplished by freshly feeding loose abrasive slurry in the polishing zone between a pitch lap or polyurethane pad and the workpiece. To achieve the desired surface quality, this technique requires a long processing time and a continuous plentiful supply of slurry. Li et al. (2008) polished optics with a polyurethane pad and eliminated surface damage several hours later, thereby mitigating subsurface

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Nomenclature

α	index of pressure in the *MRR* model proposed for MCF polishing
A_i	pressure/shear stress measurement area at step i (mm^2)
β	index of shear stress in the *MRR* model proposed for MCF polishing
C_p	coefficient in Preston's equation in conventional polishing processes
C_{pmcf}	coefficient in the *MRR* model proposed for MCF polishing
d	distance from the spot centre (mm)
Δ	working gap between the MCF slurry carrier and the workpiece (mm)
δ	clearance between the MCF slurry carrier and the magnet (mm)
F_n	normal force (N)
$F_{n,i}$	normal force at step i (N)
$f_{n,i}$	normal force increment at step i (N)
F_t	shear force (N)
$F_{t,i}$	shear force at step i (N)
$f_{t,i}$	shear force increment at step i (N)
h	the carrier shifting interval (mm)
i	pressure/shear stress measurement step number
j, k, l	number of position d
MR_d	material removal at radial position d (μm)
$MR_{\max}$	maximal material removal (μm)
MRR	material removal rate (μm/min)
$MRR_{\text{cal\_}d}$	calculated material removal rate at radial position d (μm/min)
MRR_d	material removal rate at radial position d (μm/min)
n_c	MCF slurry carrier rotational speed (rpm)
n_m	magnet revolution speed (rpm)
P	pressure (MPa)
P_i	pressure at step i (MPa)
P_d	pressure at radial position d (MPa)
r	magnet eccentricity (mm)
τ	shear stress (MPa)
τ_i	shear stress at step i (MPa)
τ_d	shear stress at radial position d (MPa)
V	relative velocity between the polishing tool and the workpiece (mm/min)
V_d	relative velocity between the polishing tool and the workpiece at radial position d (mm/min)

damage and achieving surface roughness of approximately 1 nm. Consequently, traditional nano-polishing is a costly and time consuming process. Maintaining the required quantity of active abrasive slurry and ensuring that abrasive particles are uniformly distributed within the polishing zone are among the main difficulties. Therefore, novel polishing methods that supply large amounts of uniformly-distributed abrasive particles in the polishing zone are of high priority.

One promising advanced finishing technique is magnetic field-assisted polishing using magnetic fluids (MFs) or magnetorheological (MR) fluids. In this technique, the behaviour of the abrasive particles is controlled by an applied magnetic field to achieve a nano-precision-polished surface with no surface and/or subsurface damage. Tani et al. (1984) developed a polishing method based on magnetohydrodynamic behaviour of MFs. They blended SiC grains into an MF and achieved an appreciable stock removal rate greater than 2 μm/min and surface roughness less than $R_{\max}$ = 0.04 μm for finishing of acrylic resin. Umehara et al. (1995) studied the behaviour of abrasives in an MF during polishing and reported that the number of abrasives on the work surface could be controlled by a magnetic field. Prokhorov and Kordonski (1992) proposed a novel magnetorheological finishing (MRF) technique in which the MR fluid contained magnetic carbonyl-iron-particles (CIPs), abrasive grains, carrier fluid and stabilizers. Kordonski and Jacobs (1996) revealed that the MR fluid becomes viscous and morphs into a kind of Bingham fluid under an applied magnetic field. This mechanism of material removal in the polishing zone is considered as a process governed by the particularities of the Bingham flow. They obtained the shear stress distribution from the experimental measurements of the pressure distribution in the polishing spot. Golini et al. (1999) commercialized the MRF technique for optical fabrication and reported that this technique eliminates subsurface damage, smoothes root mean square (rms) microroughness to less than 1 nm, and corrects PV surface figure errors to λ/20 in minutes. Shorey et al. (2001) measured the drag force in MRF involving a sapphire workpiece and found that there is a linear relation between the material removal rate (*MRR*) and the drag force in MRF. Miao et al. (2009) demonstrated how the calculated shear stress governs the material removal in MRF of optical glasses based on their mechanical properties and incorporated the shear stress and material mechanical properties into a modified Preston's equation. Miao et al. (2010) also investigated the effect of process parameters (nanodiamond concentration, penetration depth, the relative velocity between the part and the MR fluid and magnetic field strength) on *MRR* in MRF of borosilicate glass (BK7). They found that shear stress is independent of the process parameters. The volumetric removal rate (*VRR*) is only insensitive to the magnetic field strength. Thereby, the *MRR* model for MRF was expanded by including nanodiamond concentration and penetration depth. Jha and Jain (2004) developed a new magnetorheological abrasive flow finishing (MRAFF) process for complex internal geometries using MR fluid. They demonstrated that the roughness reduces gradually with the increase of magnetic field strength and validated the role of rheological behaviour of MR fluid in exerting finishing action. Das et al. (2008) performed the theoretical investigations into the mechanism of MRAFF process and concluded that shearing action takes place during finishing when the shear force acting on the abrasive particles is greater than the reaction force due to the strength of the workpiece material opposing material removal. Das et al. (2011) also experimentally characterized rheological properties of MR fluid in MRAFF process. They described that the MR fluid in MRF, MRAFF and similar other processes is a suspension of micron-sized magnetizable particles such as CIPs and non-magnetic abrasive particles dispersed in either an aqueous or non-aqueous carrier fluid like paraffin oil, silicone oil, mineral oil, or water and stabilizing additives. They observed that magnetic field has the highest contribution on the yield stress and viscosity of MR fluid than the volume concentrations of CIPs, abrasive particles and grease. Cheng et al. (2009) polished aspherical optical components with an MR fluid using a 2-axis wheel-shaped tool supporting dual magnetic fields, improved the surface roughness from 3.8 nm to 1.2 nm after 10 min of pre-polishing and corrected form errors from an rms value of 2.27 μm to 0.36 μm after 60 more minutes of fine polishing. By analyzing MRF processes, Dai et al. (2010) established a calibrated predictive model of material removal function by introducing an efficiency coefficient, thereby improving finishing determinacy and model applicability. Sidpara and Jain (2011) measured the normal and tangential forces in MRF. They concluded that maximum contribution is made by a working gap on the forces developed on the workpiece surface followed by CIPs concentration, whereas minimum contribution is noted by the wheel speed. Singh et al. (2012) proposed a nano-finishing process using a ball end MRF tool and applied it to flat as well as 3D ferromagnetic work surfaces, thus verifying that the newly developed method