Full Aperture Optical Polishing Process: Overview and Challenges

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Abstract The aim of advanced optical fabrication is to produce highly accurate optical surface with better reproducibility. It demands a good control and systematic understanding of the process and its parameters. Optical polishing process defines the final surface figure and finish of the component. Controlled amount of finishing forces and material removal rate are necessary for polishing of brittle materials. However, the conventional or full aperture polishing process still depends on the operator's skills to achieve the desired surface figure and finish. The process may be well optimized at individual manufacturing setups but there appears to be a little prediction about polishing outputs. Thus, it is essential to study the fundamental mechanisms of material removal during polishing in order to achieve the accurate prediction of process outputs. This paper reviews the work carried out in the area of full aperture optical polishing.

Keywords Brittle · Finishing · Lapping · Material removal · Optical · Polishing

Symbols

R_a	Average surface roughness
k	Preston's constant
P	Pressure
V	Relative velocity
E	Workpiece Young's modulus
ρ_w	Wafer density
N	Number of active abrasives
V_{rem}	Volume removed by single abrasive

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n Number of effective abrasive particles
δ_{aw} Penetration depth of single abrasive particle into the wafer-abrasive interface
R_{aw} Radius of contact area of a single effective abrasive at wafer-pad asperity interface
C Constant
x Slurry concentration

1 Introduction

Fabrication of optical grade surfaces (surface figure < 0.1 µm peak to valley, $R_a < 30$ nm) have always been a challenge. Highly polished surfaces are demanded in optical systems where lasers are involved, as the optical surface has to either transmit or reflect high amount of energy. Rough surface may lead to scattering of light or deformation of surface due to absorption of energy because of surface defects (scratch and digs), which may even lead to failure of components. High precision surfaces are also required where the intensity of incoming light signal is quite low, for example telescope. Loss of signal, due to scattering of light from surface defects, cannot be afforded. Other applications, where highly polished optical surfaces are required, are head up display and helmet mounted display for avionics applications, surgical microscopes, optical navigation systems, etc.

The polishing process is basically a surface smoothing operation used to produce high quality surface (Liang et al. 1997; Chekina et al. 1998). It removes the sub-surface damage or surface scratches produced during the grinding process and to improve the final surface figure. Although the process is very precise and of high significance, there is not much research done in this process. It has been considered as an art more than science (Marinescu et al. 2007). Basically the polishing setup involves rotating a workpiece by giving linear strokes against a rotating polisher with abrasive slurry fed continuously at the interface (Fig. 1a). The center distance between workpiece and polisher and stroke length may be varied in order to achieve

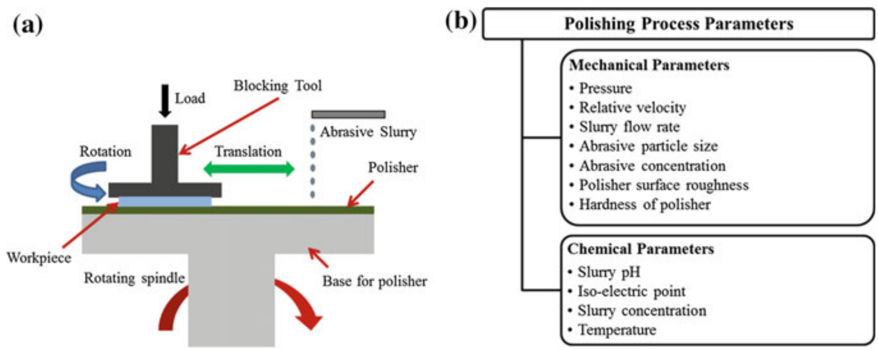

Fig. 1 **a** Schematic of polishing setup. **b** Polishing process parameters

variable relative motion. Polisher is a layer of viscoelastic material; optical pitch and polyurethane pads are commonly used polishers. But optical pitch is still preferred for high precision applications.

The chemical interactions between the slurry medium and workpiece surface prepare the surface for polishing (Lei and Luo 2004; Bozkaya and Müftü 2009). Apart from this, the workpiece-polisher interface also experiences the effects of contact and lubrication. The asperities on the polisher surface provide a seat for free abrasives and retain them during polishing. There is a three-body contact as abrasive particle gets confined between the polisher and workpiece surface, and a two body contact of the workpiece and polisher which are responsible for physical material removal (Chauhan et al. 1993; Marinescu et al. 2004). The pressure applied over the workpiece gets distributed non-uniformly over workpiece-polisher interface, which when combine with rotation of polisher, creates an interfacial dynamic friction which tends to remove the material (Suratwala et al. 2010, 2012). The polishing process has smaller material removal rate (MRR) when compared to lapping, so it is good for brittle materials. Being a free abrasive process, the fundamental mechanism of material removal during polishing is still not well understood (Xin et al. 2010; Kimura et al. 2012; Daniel Waechter and Fritz 2013). There are number of process parameters (Fig. 1b) which affect the polishing process outputs i.e. surface figure and surface finish.

A systematic understanding of process parameters is crucial for process to be more repeatable, less tedious and more economic. Various hypotheses have emerged over time to understand the process better and utilize it in the best possible way. This paper reviews these material removal hypotheses and the effects of various process parameters on polishing outputs such as surface quality and MRR in optical polishing process.

2 Workpiece-Polisher Interface (WPI)

Based on type of contact between workpiece and polisher surfaces, WPI has been modeled in three modes: contact mode, hydroplaning mode, and mixed mode (Fig. 2) (Lai 2001). In contact mode, direct surface contact of workpiece and polisher leads to higher friction coefficient generally high of the order of 0.1. In

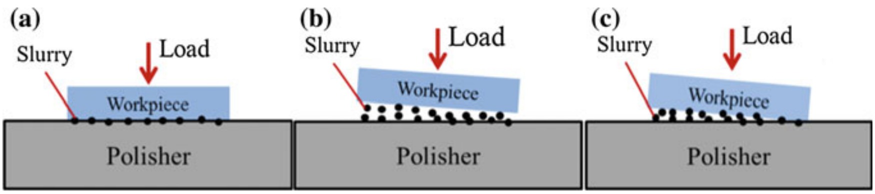

Fig. 2 Types of interfacial contact between workpiece and polisher: **a** contact mode, **b** hydroplaning mode, and **c** mixed mode

hydroplaning mode, as there is no direct contact between workpiece and polisher, friction coefficient is very small in the range of 0.001–0.01. Mixed mode is a transition from hydroplaning mode to contact mode. The friction coefficient is generally in the range of 0.01–0.1. Thus, it is the friction coefficient which characterizes the interfacial contact conditions. Modeling has been done by different researchers taking various contact conditions at the interface.

3 Material Removal and Effects of Process Parameters

The first fundamental model for material removal during glass polishing was proposed by Preston (1927) based on macro level material removal:

$$MRR = kPV \tag{1}$$

This equation has been used widely and further lot of research work was carried out using this equation as reference. But the Preston's equation is a very basic model for MRR considering only pressure and relative velocity. It was further modified by researchers. Brown et al. (1982) proposed a model based on Hertz theory which replaced Preston's constant by (1/2E) as:

$$MRR = PV/2E \tag{2}$$

Cook et al. (1990) suggested that at molecular level, material removal is accomplished mainly through chemical actions. Material removal takes place as slurry particles react with glass surface and take out silica molecules. Xie and Bhushan (1996) informed that the surface roughness increased with increase in particle size and pad hardness during free abrasive polishing and normal contact pressure has little effect on surface roughness. Tseng and Wang (1997) developed a model on the basis of the analogy of polishing process to traveling indenters:

$$MRR = kP^{\frac{5}{6}}V^{\frac{1}{2}} \tag{3}$$

Zhang et al. (1999) proposed another model considering normal and shear stress acting at interface of abrasives and workpiece surfaces:

$$MRR = k\sqrt{PV} \tag{4}$$

Luo and Dornfeld (2001) proposed a model based on plastic contact at wafer-abrasive and pad-abrasive interfaces considering a normal distribution of particle size and a uniform pad roughness distribution:

$$MRR = \rho_w N V_{rem} \tag{5}$$

In the model, apart from pressure and relative velocity, they also took wafer, pad and abrasive properties into consideration for predicting MRR. Guanghui et al. (2001) developed a model for material removal during Chemical mechanical polishing (CMP), where the abrasive particles abrade the hydroxylated layer which was modeled as a perfectly plastic material and deformation profile of soft pad was modeled as bending of thin elastic beam. The two different regimes of material removal were explored based on relatively stiff pad and high abrasive concentration in which pad and wafer do not contact each other and entire load is transferred through abrasives, and second one in which soft pad and low abrasive concentration was considered. It was confirmed that most of the CMP operations follow the soft pad-low abrasive concentration model for material removal where MRR varies as $P^{9/8}V$ for spherical particles but as $P^{3/4}V$ for sharp particles.

Evans et al. (2003) discussed various mechanism of material removal during lapping and polishing processes. Four main material removal hypotheses were summarized: (a) *the abrasion hypothesis*, in which material removal is achieved by inducing very fine cracks on the glass surface; (b) *the flow hypothesis*, linking plastic material displacement with local material softening due to the frictional heating; (c) *the chemical hypothesis*, in which material removal is attributed to the formation and removal of a layer of gel; and (d) *the friction wear hypothesis*, developed in response to the lack of information provided by the chemical hypothesis regarding the influence exerted by the polishing medium.

Terrell and Higgs (2006) reviewed the studies of slurry hydrodynamics which gave significant insight into some of the phenomenon behind polishing hydrodynamics but the studies did not consider rotation of wafer, deflection of pad and wafer, etc. which made them concluded that the studies were insufficient to completely explain the dynamic behavior of slurry in CMP. Jeng and Huang (2005) suggested a CMP material removal model based on micro-contact mechanics also considering the effect of abrasive particles, which was ignored in other studies:

$$MRR = n\delta_{aw}R_{aw}V \tag{6}$$

Lin et al. (2009) developed a two-dimensional quasi static finite element contact model to study von Mises stress distribution on wafer surface and reported the similar results for relationship with MRR as Wang et al. (1997). Bozkaya and Müftü (2009) proposed a material removal model based on the contact mechanics of pad, abrasives and wafer. The model was developed by considering a contact regime at the pad-wafer interface. Lubrication effects were neglected and MRR was assumed to be linearly dependent on relative velocity. The model developed depicted non-linear relationship between MRR and pressure applied with exponent lying within 0.85–1.1. The model depicted a linear relationship of MRR with abrasive concentration when small, and tends to be stable after that until a critical concentration level after which MRR starts decreasing with further increase in abrasive concentration. Ludwig and Kuna (2012) studied the contact pressure distribution between pad and wafer in CMP process using an analytical approach based on plate theory to describe the behavior of the carrier.

Lin (2007) presented an analytical model based on elastic-plastic contact mechanics for predicting MRR during polishing:

$$MRR = CPVx^{\frac{2}{3}} \tag{7}$$

The model was based on abrasive wear theory and described as advancement to Preston's model revealed that the MRR is proportional to pressure and the workpiece-pad relative velocity and also proportional to the two-third power of volume concentration of slurry particle.

Wang et al. (2007) reported some controversial results that the material removal increased when the ceria particles concentration was decreased from 1 to 0.25 wt% during optical CMP which was explained to be a quantum phenomenon. Zhang et al. (2010) stated that MRR increased linearly with increase in abrasive concentration till 20 wt% and then became stable. Park et al. (2008) investigated the correlation between the spatial distribution of pad surface roughness and the material removal profile for CMP and reported that there is a higher MRR at the wafer center because of accumulation of ceria particles at the center which also increase the roughness of the pad. Lien and Guu (2008) used Taguchi technique and Analysis of Variance (ANOVA) to optimize the polishing process parameters for glass substrate reported that "surface finish is significantly affected by platen speed followed by applied pressure, speed and time."

Belkhir et al. (2009) observed that during polishing process friction coefficient increases initially for some time and then tends to be stable. They reported an inverse relationship of friction coefficient with velocity and concluded that pad properties are responsible for variation in friction coefficient. Kelm et al. (2012) investigated variation of friction coefficient in polishing process and presented a method to measure the friction coefficient using an offset tool which is based on measuring the effective electric power from the polishing tool. It was concluded that material removal in polishing process depends upon variation in friction coefficient between workpiece and polisher. Suratwala et al. (2010) investigated ceria pad polishing of fused silica glass and proposed a model for predicting material removal and surface figure as a function of kinematics, loading conditions and polishing time. It was indicated that pressure distribution over the workpiece is non-uniform and a complex parameter which is not well understood. Tian et al. (2013) investigated and optimized the CMP for glass substrate and reported that pad rotational speed, polishing head rotational speed and down force significantly affect surface roughness, surface figure and MRR. Recently Belkhir et al. (2014) conducted a study to understand the relationship between the polishing pressure, contact surface, and friction coefficient during the optical polishing, which was based on direct measurement of the mentioned parameters. It was reported that contact surface and pressure distribution affect the glass surface shape and frictional behavior which influences the material removal mode during the process.

Authors have carried out polishing experiments on BK7 optical glass using Taguchi's method taking abrasive slurry concentration, pressure and relative

Fig. 3 **a** Workpiece before lapping process; **b** workpiece after lapping process; **c** full-aperture polishing machine; **d** pitch polisher used for polishing; **e** workpiece surface after 2 h of polishing

velocity as variable parameters (Fig. 3). It is observed that abrasive slurry concentration plays the most significant role in determining MRR and R_a. Pressure is observed to have little effect on R_a.

4 Discussion and Conclusion

Polishing process can produce precision optical surface for high end applications. However to make the process more repeatable and controlled, it is required to understand the material removal characteristics of the optical polishing process. The initial material removal models developed by researchers are similar to Preston's model which took only applied pressure and relative velocity into formulation. The major limitation of Preston's equation and its modified versions is that the parameters related to consumables (i.e. abrasive slurry and polisher) and workpiece are not explicitly defined in the equations. Thus, there was no information regarding control of these parameters. The model proposed by Brown was applicable for metals, not for glass. The models proposed by Cook and Xie and Bhushan were superior to Preston's equation as they considered consumable parameters also. Other studies were performed based on finite element modeling of WPI and elastic and elastic-plastic nature of materials to understand the behavior of process parameters. Other researchers have proposed empirical models, but are limited to their individual machine setups and not valid for generalized polishing process.

The coefficient of friction at WPI is a complex parameter and is closely related to contact pressure and relative velocity. It requires further exploration to understand the role of friction and how it varies and affects polishing outputs. The distribution of abrasive particles over the interface of workpiece and polisher significantly affects pressure distribution, coefficient of friction, MRR, and thus surface quality. Till now, researchers are not able to properly incorporate this parameter properly in their formulations.

It can be concluded that the polishing process is a very critical step of optical fabrication process, time consuming, laborious and very important. It is not an established process; material removal mechanism is still a topic of research. There are number of process parameters which affect final output but their individual and mutual effect is not clear. Different researchers have optimized process parameters but are limited to their individual setups and applicable only in certain conditions. In this paper, authors have attempted to explain the full aperture optical polishing process and have highlighted the issues involved in understanding the material removal behavior of the process.

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