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Chemical mechanical polishing of polymeric materials for MEMS applications

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Abstract

Polymeric materials such as polycarbonate (PC) and poly-methyl methacryate (PMMA) are replacing silicon as the major substrate in microfluidic system fabrication due to their outstanding features such as low cost and good chemical resistance. In this study, chemical mechanical polishing (CMP) of PC and PMMA substrates was investigated. Four types of slurry were tested on CMP of the polymers under the same process conditions. The slurry suitable for polishing PC and PMMA was then chosen, and further CMP experiments were carried out under different process conditions. Experimental results showed that increasing table speed or head load increased the material removal rates of the polymers. The polymeric surface quality after CMP was acceptable to most MEMS applications. Analysis of variance was also carried out, and it was found that the interaction of head load and table speed had a significant (95% confidence) effect on surface finish of polished PMMA. On the other hand, table speed had a highly significant (99% confidence) effect on surface finish of polished PC.

Keywords: Polycarbonate; Poly-methyl methacryate; Chemical mechanical polishing; Material removal rate; Surface roughness; Analysis of variance

1. Introduction

In an article entitled 'Silicon as a micromechanical material', Petersen [1] described techniques for micro-electro-mechanical systems (MEMS) fabrication. Processing of silicon wafers has played an enhanced role in manufacturing of MEMS [2]. On the other hand, increasing demands for high electrical performance have led to significant advances in integrated circuit (IC) fabrication and microelectronics packaging [3–5].

Technical advances inspired the development of chemical mechanical polishing (CMP) for IC fabrication at IBM [6,7]. As semiconductor chips are highly integrated, more precise planarization of each layer on chips is needed [8]. Interlevel dielectric planarization by CMP is necessary for technologies beyond the 0.35-μm CMOS (complimentary metal-oxide semiconductor) generation [9]. CMP has emerged as the preferred manufacturing process for planarizing multi-level metal layers in ICs [10,11], although diamond grinding can also generate mirror surfaces on brittle materials including silicon [12–17].

A dielectric constant $k<3$, gap filling at high aspect ratios [18], and global planarization are challenging demands for dielectrics in conventional multilevel metallization schemes of modern IC technologies [19]. Novel IC devices based on structures of low-k material/Cu have been proposed recently using the CMP technology [20]. However, reduction of scratches is required in advanced CMP processes [21]. Ultra-low-k dielectrics are prone to damage during CMP. Most ultra-low-k materials are also attacked by CMP or post-CMP cleaning chemicals [22]. Other CMP applications include polishing of $Ba_{0.6}Sr_{0.4}TiO_3$ for ferroelectric random access memory applications [23] and SiLK dielectric planarization [24].

For MEMS applications, CMP processes have also been developed for planarizing silicon dioxide and metal layers [25]. CMP is used to achieve flat, mirror-like surfaces for optical devices, planarize the topology from previous manufacturing steps, and reduce film roughness for more precise lithography or for wafer bonding [26].

Traditionally, silicon and glass have been the major materials used in MEMS [27]. However, many biomedical

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devices require soft or polymeric materials such as polycarbonate (PC) and polyimide. Polymers are inexpensive and can be used in disposable devices, relaxing stringent sterilization-on-reuse requirements. They provide a more suitable interface with biological tissue [28]. Soft materials have many attributes that make them ideally suited for defining microfluidic, optical and nanoelectromechanical structures with low-cost replication processes [29].

Therefore, further developments have focused on substituting silicon and silicon dioxide with polymers in recent years. For semiconductor devices, polymers excel due to their relatively low dielectric constants, minimized interconnection delays and improved conductor-packaging density. In MEMS, the use of polymers is mostly aimed at creating high-aspect-ratio structures [8].

Microfluidics [30,31], a MEMS technology, enables the fabrication of networks of channels, chambers, and valves to control the flow of liquids in amounts as minute as one picoliter. Chemical analysis, drug delivery, biological sensing and environmental monitoring typically incorporate MEMS microfluidic devices [32].

Recent developments in MEMS fabrication techniques have moved away from the mask/etch paradigm and instead exploit properties of polymers. Imprinting techniques can be used to fabricate microfluidic devices on poly-methyl methacryate (PMMA) substrates [33]. When choosing a polymer-based substrate, its properties are critical for the fabrication process and successful application of the device [34]. Because of their properties like fine resolution and stability, PMMA and PC are also common materials for many other applications [35,36].

In a CMP process, one polishing condition can result in a large difference in material removal rates (MRRs), which influence other important aspects of a CMP process, such as planarization efficiency [37]. Major process parameters of CMP are slurry, polishing pressure, polishing pad material, polishing pad and workpiece spinning speeds. The success of CMP depends on selection of process parameters [38].

Common problems encountered in using CMP arise from lack of predictive capability regarding the MRR and its dependence on various parameters, and difficulties in removal of colloidal particles adhering to the workpiece surface after polishing [30]. The demand of lithographic exposure resolution increases when component sizes decrease. The global planarization technology becomes increasingly important, although CMP may also introduce surface defects and increase the demand for automatic defect-detection techniques [39]. CMP mechanisms are very complicated and not understood clearly yet. It is extremely difficult to analyze its polishing mechanisms [40,41]. Therefore, experiments are conducted repeatedly to ensure the best process conditions [42].

Reports on CMP of polymeric materials are still scarce, compared to reports on CMP of silicon wafers. In this study, CMP of PC and PMMA substrates was investigated. Four types of slurry were tested on CMP of these polymers under the same process conditions. The slurry suitable for polishing PC and PMMA was then chosen, and further CMP experiments were carried out under different process conditions to study the effects of two key process parameters on CMP of PC and PMMA.

Table 1
Parameters and their settings for the CMP experiments

Parameter	Setting (experiment 1)	Setting (experiment 2)
Process time (min)	1	1
Table speed (rpm)	30	20, 30, 40
Oscilation speed (mm/sec)	2	2
Spindle speed (rpm)	40	40
Head load (g/cm^2)	100	75, 100, 125
Slurry flow rate (ml/min)	100	100
Slurry	Simlox, ILD 1200, Mazin SRS1 and SRS3	The slurry selected after experiment 1

2. Experiments

PMMA and PC samples were prepared by cutting them into 2-mm-thick round-shape plates with a 150-mm diameter. A face polisher was used to grind surfaces of the samples under a MD 600 polishing disc. The surface roughness after grinding was between 0.1 and 0.3 μm. The samples were then polished using specified parameters on an Okamoto SPP-600S CMP machine.

Table 1 shows the parameter settings used. The slurry flow rate was 100 ml/min, the spindle rotation speed was 40 rpm, and the oscillation speed was 2 mm/s.

In experiment 1, head load was 100 g/cm^2 and table speed was 30 rpm, which were typical polishing conditions for bulk removal of silicon using the CMP machine. Four types of slurry, namely Simlox, ILD 1200, Mazin SRS1 and SRS3, were evaluated and the most suitable slurry for CMP of the polymers was then selected based on analysis of MRRs and surface finish of polished samples. ILD 1200 is

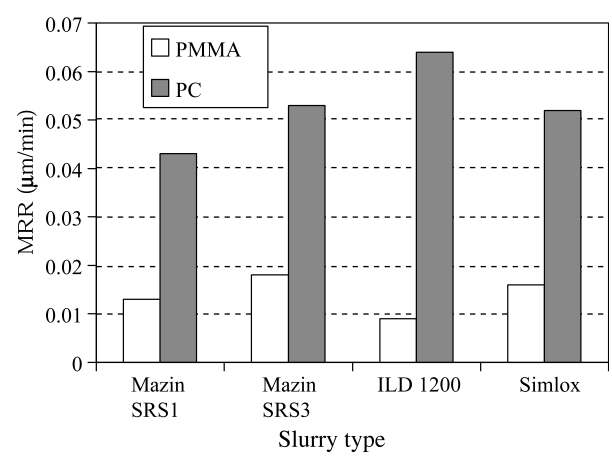

Fig. 1. MRRs of the polymers polished using the four types of slurry.

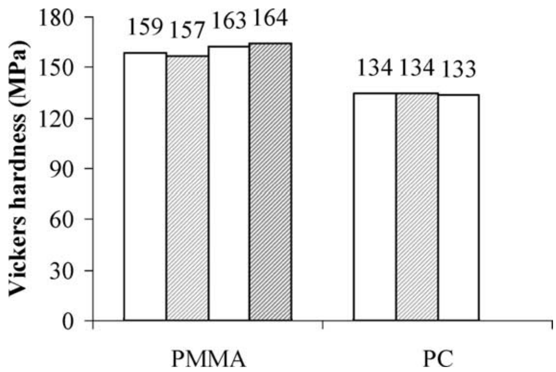

Fig. 2. Results of the material hardness test.

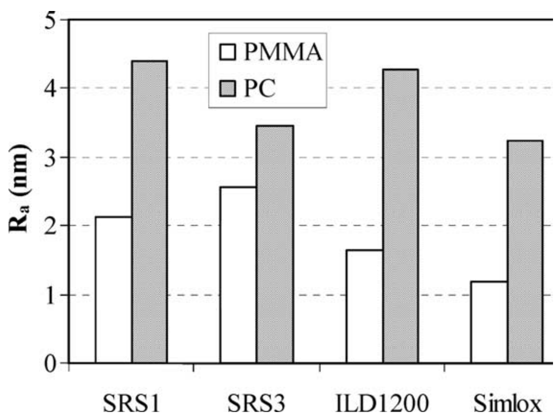

Fig. 3. Surface roughness of the polymers after CMP using four types of slurry.

fumed silica polishing slurry containing ammonium hydroxide. Mazin SRS1 and SRS3 are colloidal silica polishing slurry for stock removal applications. Okamoto Simlox A1136 is slurry designed for removal of polymeric materials.

In experiment 2, two key process parameters, head load and table speed, were varied to examine their effects on polishing efficiency and quality. To limit the number of experiments, three levels (low, median and high) for each parameter were assigned: 75, 100 and 125 g/cm^2 for head load, and 20, 30 and 40 rpm for table speed. The slurry selected after experiment 1 was used.

Before and after polishing, the thickness of samples was measured using a head thickness gauge to compute the MRR, which was defined to be the thickness reduction per minute in this study. After CMP, surface roughness of samples was measured using an atomic force microscope (AFM), and the arithmetic average roughness R_a and the root-mean-square roughness R_q were obtained. AFMs are widely used for characterization of smooth surfaces [43] and inspection of surface deformations [44].

3. Results and discussion

Fig. 1 shows measured MRRs of the polymers polished using the four types of slurry. MRRs of PMMA are between 0.009 and 0.018 μm/min, which are much lower than those of PC (0.043–0.064 μm/min). This significant difference results from the difference of material hardness. Material hardness of the polymers was measured using a Vickers hardness tester and the results are shown in Fig. 2. The average hardness of PMMA and PC substrates used in our experiments was 161 and 134 MPa, respectively. PMMA is harder than PC. The MRRs of PC were seven and three times those of PMMA when ILD 1200 and Simlox were used, respectively.

The measured surface roughness of the polymers polished using the four types of slurry is shown in Fig. 3. PMMA samples are harder and after CMP have better surface finish (lower R_a values) than PC samples polished

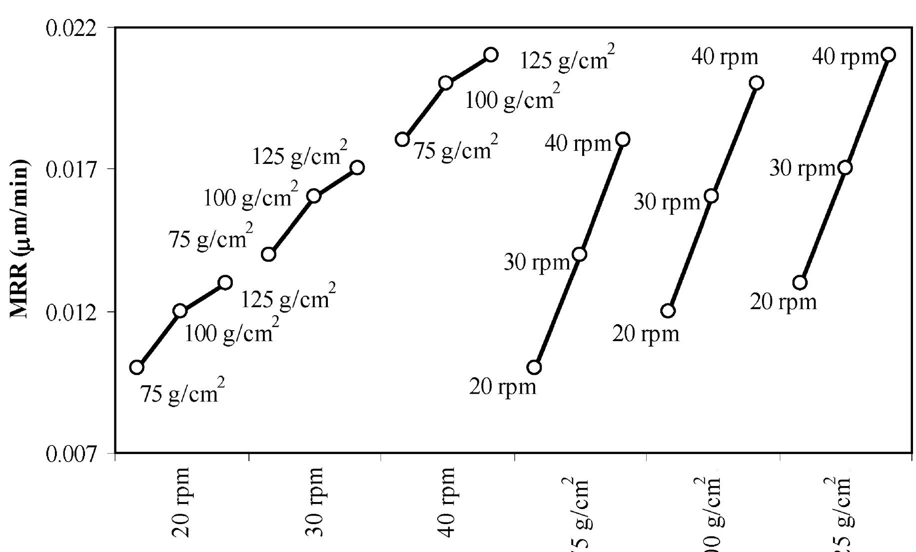

Fig. 4. Effects of head load and table speed on MRRs of PMMA.

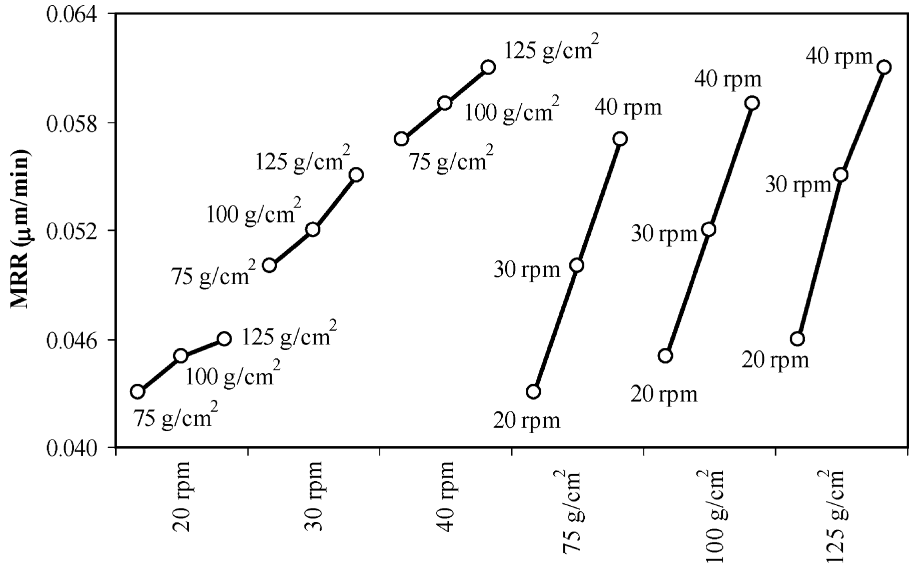

Fig. 5. Effects of head load and table speed on MRRs of PC.

under the conditions used. The smoothest PMMA and PC surfaces were obtained by CMP using Simlox.

Figs. 1 and 3 do not indicate which slurry is the most effective in polishing both polymers and at the same time can produce the best surface finish. However, Simlox produced relatively high MRRs and the lowest surface roughness values in polishing the polymers. Therefore, it was selected to be the CMP slurry, and was used in experiment 2 to evaluate effects of two key process parameters.

Figs. 4 and 5 show the effects of head load and table speed on MRRs in polishing of PMMA and PC. MRRs increase with increased head load and table speed. The results approximately agree with the Preston Equation [1,6]:

$$\mathrm{MRR} = K_p P \frac{\Delta s}{\Delta t} \tag{1}$$

Where P is the pressure, $\Delta s/\Delta t$ is the linear velocity of the pad relative to the workpiece and K_p is the Preston coefficient. Another trend revealed from the two figures was that within the chosen experimental parameter ranges, the variation of table speed introduced a more significant change in MRRs than that of head load.

Surface roughness of polished PMMA and PC samples is shown in Figs. 6 and 7, respectively. Figs. 8 and 9 show examples of AFM images of polished polymers. These figures show that the softer polymer (PC) after CMP had deeper micro scratches than the harder polymer (PMMA) after CMP, and therefore had higher surface roughness values. However, all of polished PMMA and PC surfaces had nanometer-order surface roughness heights. In general, the surface quality after CMP appeared to be acceptable to most MEMS applications. However, intensive post-CMP cleaning was required to get rid of particles and chemical remains introduced by the CMP process.

Directly from Figs. 6 and 7, it is difficult to draw any conclusions whether there are any significant effects of head load and table speed on surface roughness of polished

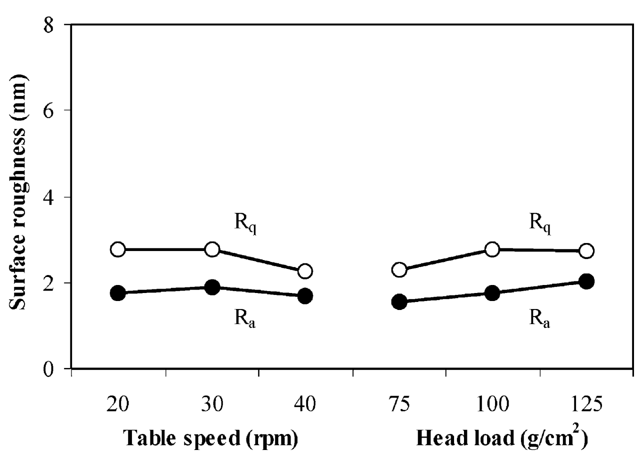

Fig. 6. Effects of head load and table speed on surface finish of polished PMMA.

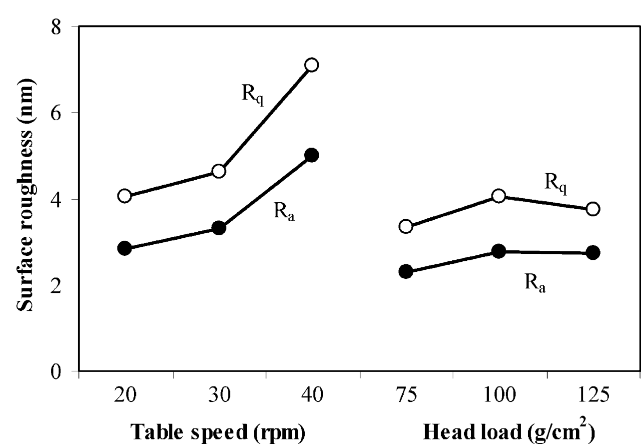

Fig. 7. Effects of head load and table speed on surface finish of polished PC.

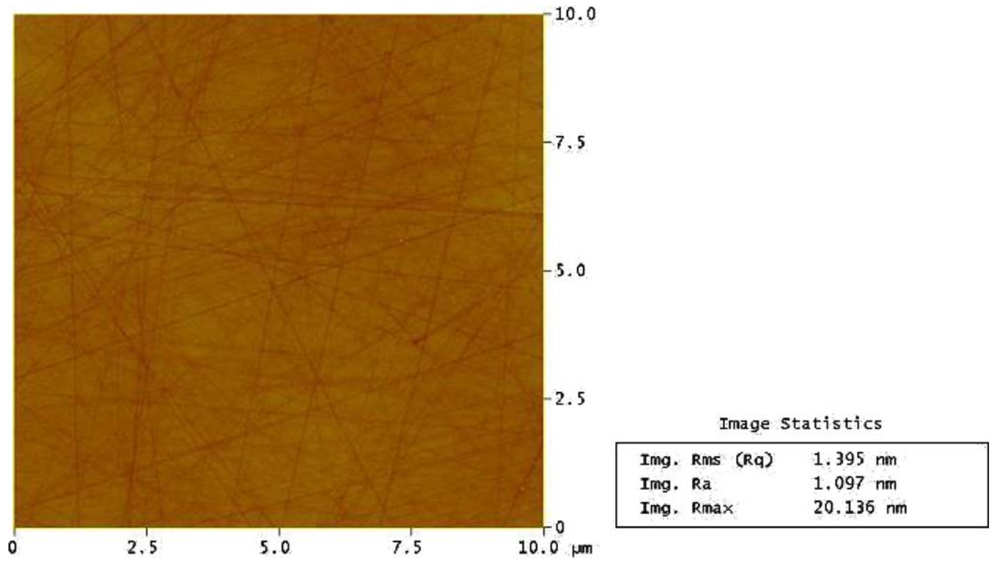

Fig. 8. AFM image of PMMA polished using Simlox, table speed = 20 rpm, and head load = 75 g/cm^2.

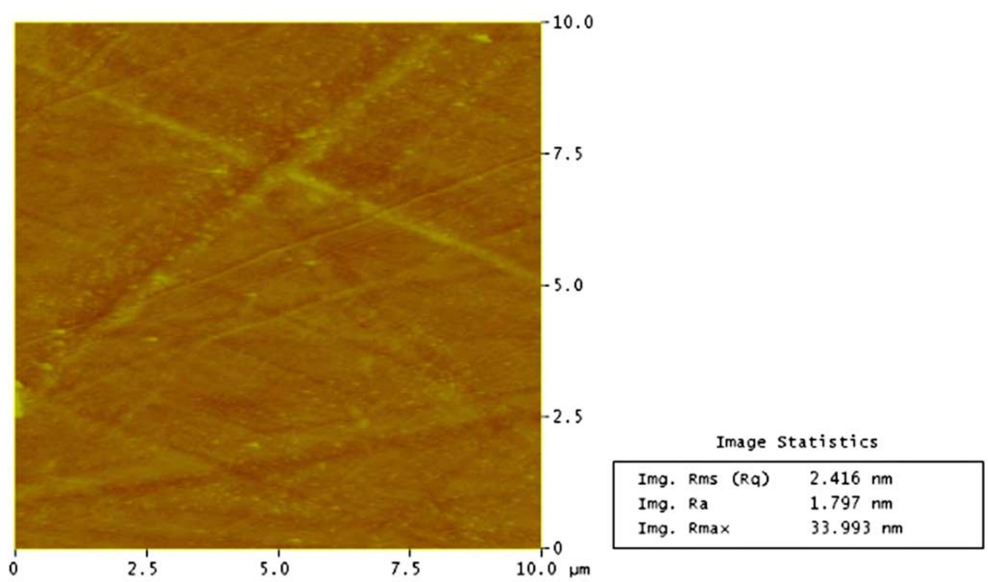

Fig. 9. AFM image of PC polished using Simlox, table speed = 20 rpm, and head load = 125 g/cm^2.

PMMA and PC. Therefore, analysis of variance (ANOVA) of the two-factor factorial experiments was carried out using the measured surface roughness values to investigate the effects on surface finish of polished PMMA and PC, as shown in Tables 2 and 3, respectively. The summary of the ANOVA results is shown in Table 4.

It was found that only the interaction of head load and table speed had a significant (risk $\alpha = 0.05$, 95% confidence) effect, and individual head load and table speed had no significant effects on surface finish of polished PMMA samples. On the other hand, only table speed had a highly significant ($\alpha = 0.01$, 99% confidence) effect, and individual head load and the interaction of head load and table speed

Table 2
ANOVA table for PMMA

Source of variation	Sum of squares	Degrees of freedom	Mean square	*F* value
Table speed	0.498	2	0.249	0.346
Head load	0.68	2	0.34	0.472
Interaction of head load and table speed	12.56	4	3.14	4.361
Error	6.48	9	0.72	
Total	20.184	17		

Table 3
ANOVA table for PC

Source of variation	Sum of squares	Degrees of freedom	Mean square	*F* value
Table speed	22.788	2	11.394	8.421
Head load	2.354	2	1.177	0.870
Interaction of head load and table speed	10.232	4	2.558	1.891
Error	12.176	9	1.353	
Total	47.55	17		

Table 4
Summary of ANOVA results

Level of effect	Factor	Material	
		PMMA	PC
Significant ($\alpha=0.05$)	Table speed	No	Yes
	Head load	No	No
	Interaction	Yes	No
Highly significant ($\alpha=0.01$)	Table speed	No	Yes
	Head load	No	No
	Interaction	No	No

had no significant effects on surface finish of polished PC samples.

4. Conclusions

Four types of slurry were used as abrasives and experiments of CMP of PMMA and PC were conducted under the same process conditions. The MRRs and surface roughness of PC were found to be much higher than those of PMMA due to different material hardness, regardless of the types of slurry used. Material hardness of PMMA (161 MPa) is higher than that of PC (134 MPa). Simlox slurry was found to be suitable for CMP of the two polymers. Then, CMP of PMMA and PC was performed by varying two key process parameters, namely table speed and head load while other parameters were kept constant. The MRRs were significantly affected by table speed and head load. Increasing table speed or head load will increase MRRs. All polished PMMA and PC surfaces had nanometer-order surface roughness heights, acceptable to most MEMS applications. ANOVA was also carried out, and it was found that the interaction of head load and table speed had a significant (risk $\alpha=0.05$, 95% confidence) effect on surface finish of polished PMMA samples. On the other hand, table speed had a highly significant ($\alpha=0.01$, 99% confidence) effect on surface finish of polished PC samples.

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