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REGULAR PAPER

Center-injected Polishing for Efficient Slurry Utilization

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Abstract

Polishing is one of the most crucial finishing processes and usually consumes a sufficient slurry to achieve an ultra-fine surface. However, excess slurry consumption is environmentally costly, as it generates a large amount of wastewater. Given the growing environmental concerns, it is essential to improve the process efficiency and minimize the environmental burdens. Considering this, a novel polishing system, herein referred to as center-injected polishing, is proposed by injecting slurry into the center of the polishing pad. Here, it is aimed to utilize the centrifugal force of the rotating pad, with the aim of efficient slurry utilization. The slurry is directly introduced between the pad and the workpiece, then dispersed across the pad by centrifugal force. A simple experiment was conducted with computational analysis using the specially designed polishing tool to prove the concept; slurry was distributed more uniformly in center-injected polishing when compared to the conventional process. The polishing system was then constructed to evaluate polishing performances. Based on sets of experiments in the polishing of silicon carbide (SiC), slurry efficiencies and productivity were analyzed with respect to different rotational speeds and slurry supply rates. The material removal rate (MRR) was more than twice the rate achieved by conventional polishing at the same processing conditions; whereas the slurry consumption was approximately 60% less at the same MRR. The extended Preston equation was used to predict the MRR of the new process. It is expected that efficient slurry utilization will reduce the environmental footprint of abrasive processes.

Keywords Polishing · Slurry Consumption · Process Efficiency · Specific Energy Consumption

1 Introduction

Polishing is important when a finely finished surface is necessary. Slurry is introduced between the workpiece and tool, and material is removed by abrasives that act on the workpiece [1]. Usually, slurry is delivered in excess because the primary goal is achievement of an ultra-fine surface. However, this excess slurry is environmentally costly. Polishing usually requires substantial time and effort considering the low process throughput [2–4]. It generates a large amount of wastewater containing chemicals and abrasive particles, and post-treatment processing is necessary [5]. Given the growing environmental concerns,

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improving the process efficiency and minimizing the environmental burdens are of great importance [6, 7].

Accordingly, efforts have been made to reduce slurry consumption and improve process efficiency. Slurries with no or low levels of abrasives can reduce the environmental burden [8, 9]. Mixed abrasives [10–16] or hybrid process [17–19] can improve polishing efficiency. Various abrasive materials were evaluated with respect to their shapes and sizes [20, 21]. An effort was also made in multiphase jet rotary abrasive flow finishing [22], as well as to utilize water-soluble dicarboxylic acids in abrasive-free chemical mechanical polishing of copper [23].

However, the slurry supply method has received minimal attention; slurry is usually delivered to the perimeter of the polishing pad. Thus, only some amount of the slurry is utilized during material processing. To efficiently introduce the slurry to the pad, Liao et al. applied a crescent-shaped slurry injector just in front of the rotating pad [24]. Lin et al. developed disc hydrodynamic polishing to enhance slurry pressure and velocity via the dynamic pressure grooves by implementing spiral grooves on the polishing pad [25]. Nevertheless, it is still difficult to efficiently deliver slurry between the polishing pad and workpiece and improve polishing efficiency. Mechanical polishing usually requires higher speeds than chemical–mechanical polishing, and the centrifugal force generated by pad rotation tends to prevent slurry penetration to the center of the pad [26]. Since an insufficient slurry supply leads to lowering polishing performances, it is important to effectively introduce the necessary amount of slurry and to reduce slurry consumption without compromising process quality.

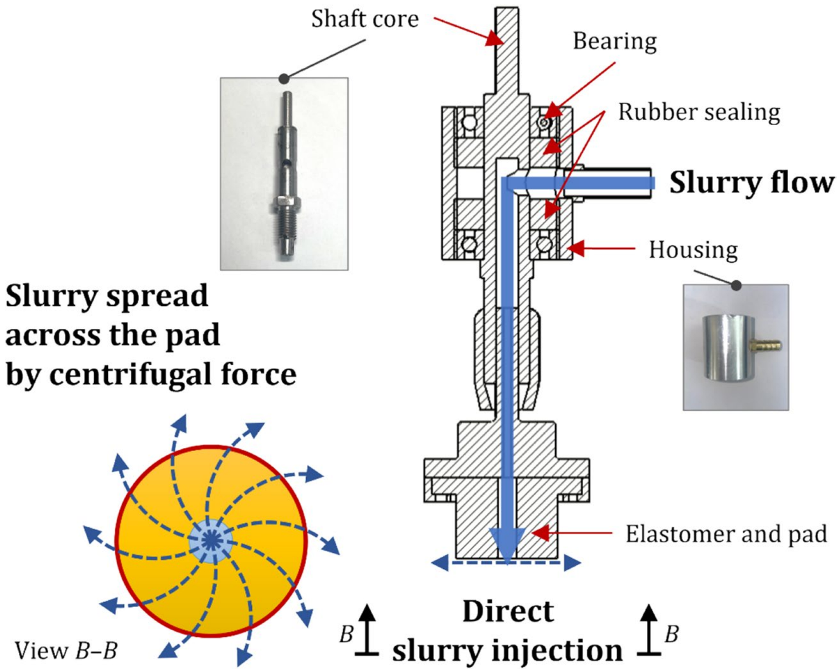
Here, we delivered slurry to the center of the polishing pad through a novel method: "center-injected polishing." It was hypothesized that the centrifugal force would spread slurry across the pad, improving process efficiency. Slurry was supplied through a rotating shaft connected to the center of the pad and directly delivered between the polishing pad and workpiece.

To implement the concept, a polishing tool was designed with a slurry supplying hole on the rotating shaft core. A simple experiment was conducted as well as computational analysis to prove the concept. The polishing system was then constructed to perform polishing experiments. This "center-injected" supply method increased the proportion of slurry that engaged in material removal. The surface roughness and material removal depth were compared with parameters of the conventional slurry supply method; slurry utilization and energy consumption were analyzed. To evaluate the polishing efficiency, slurry efficiency and specific energy consumption per unit volume of material removal were calculated. Finally, the extended Preston equation was used to predict process performance. Center-injected polishing substantially improved both slurry utilization and polishing efficiency without additional equipment.

2 Center-injected Polishing Tool

Figure 1 shows a cross-sectional schematic of the polishing tool with the rotary unit (*i.e.*, a shaft core and an outer housing). The core has a vertical hole in the center and a horizontal hole on the side. The slurry is supplied via the

Fig. 1 Cross-sectional image of polishing tool

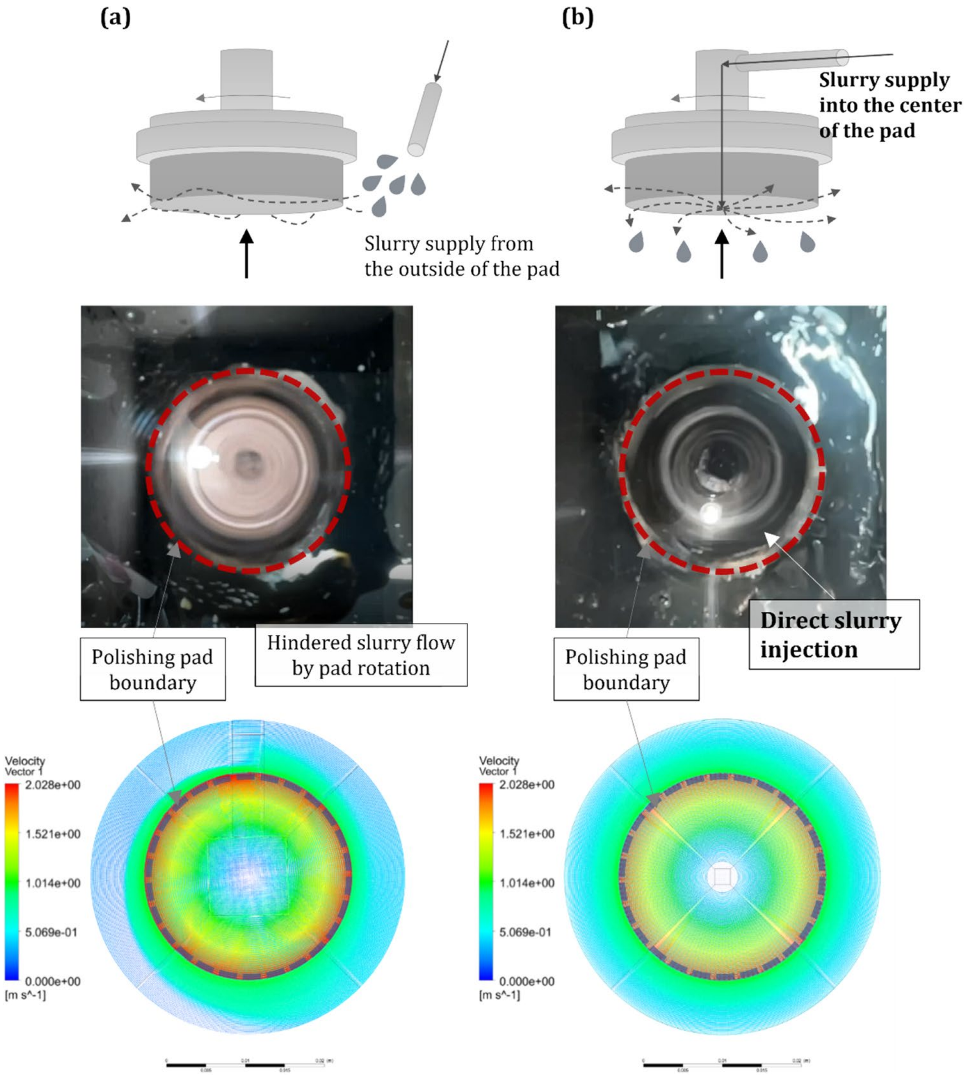


inlet port of the housing, reaches the polishing pad through the shaft core, then spread out by the centrifugal force. A peristaltic pump (BT100M, Baoding Chuangrui Precision Pump Co., Ltd., China) is used to supply slurry at a constant rate. Diamond and ceria particles with diameters < 1 μm are suspended in water at a volumetric ratio of 1:5. The slurry is adequately supplied, without substantial leakage. The 26-mm-diameter polishing pad is a 1.5-mm-thick polyurethane layer attached to a flexible polydimethylsiloxane (PDMS) cylinder that maintains constant polishing pressure. The polishing tool is connected to a spindle (SW80, SAMWOO Hitech, Korea).

Here, the center-injected polishing was compared to conventional polishing, in which slurry was supplied outside of the polishing pad (10 mm from the pad) both by computational analysis and experiments. In computational analysis, both the workpiece and the polishing pad were assumed to have flat surfaces and the fluid was assume had the same properties just as the water for simplicity. Figure 2 compares the computational fluid dynamics results derived using ANSYS; the rotating pad was observed from the bottom through a transparent workpiece. The slurry flow rate was set to be 5 ml min^{-1} and the rotational speed of the pad was 1500 rpm. K-omega SST model was used to predict the flow. In the experiments, black ink mixed with water was supplied instead of slurry to visualize liquid behavior.

During conventional polishing (Fig. 2a), slurry flow was hindered by pad rotation, as revealed by experimental and computational analyses. Only a small amount of ink was observed between the pad and workpiece. Polishing tools and slurry injecting flow intervenes with the rotational slurry flow, causing irregularity of slurry distribution as observed in the computational analysis. In contrast, during center-injected polishing (Fig. 2a), the ink was successfully supplied to the pad, and then scattered to the outside of the pad. The computational analysis also showed more uniformly distributed carrying fluid.

Fig. 2 Computational and experimental slurry behaviors observed from bottom of polishing pad during (**a**) conventional polishing and (**b**) center-injected polishing



Polishing experiments also indicated that slurry was effectively introduced between the polishing pad and workpiece. Figure 3 simply compares the surface profiles of 6H α-SiC produced by both methods after polishing for 20 min at the same position (*i.e.*, without workpiece movement) with a slurry flow rate of 10 ml min^{-1}. The surface profiles were measured using a surface profilometer (ET200, Kosaka Laboratory Ltd., Japan). In contrast to the results after conventional polishing (Fig. 3a), the surface after center-injected polishing was symmetrical. Furthermore, the polished depth increased as the rotational speed increased, implying that the pad rotatory energy was efficiently utilized for material removal.

3 Experimental Details

Figure 4 shows the polishing system configuration. The polishing tool was equipped with a gantry type 3-axis stage (JTM-30, Justek, Korea). Polishing pressure was monitored using a dynamometer (9251A, Kistler, Switzerland) and a power meter (PAC3200, Siemens, Germany). The polishing pad pressing force was set at 22.5 N (approximately 42 kPa) for all experimental conditions.

An area of 15 × 15 mm in 6H α-SiC workpiece was polished with a feed of 2.5 mm s^{-1} using a raster path with an interval of 625 µm. The path was repeated 10 times in each experiment (which required approximately 52 min). Table 1 lists the process parameters used mostly based on experiences from the system development [27] and preliminary experiments. For each experimental condition, polishing was repeated three times, and the results were averaged.

4 Results and Discussion

4.1 Surface Roughness

Both the conventional and center-injected polishing could successfully achieve fine polished surfaces. A white light interferometer (GLTECH Co., Ltd., Korea) was used to assess surface roughness at the centers of polished areas where the surface characteristics of the original workpiece were eliminated; the original SiC workpiece roughness was 1.5 µm. Center-injected polishing produced a surface with similar quality to surface produced by conventional polishing (Fig. 5). Surface roughness (R_a) ranged from 5 to 15 nm. Roughness of polished area was unaffected by tool rotational speed, slurry flow rate, or slurry supply method. The results can be supported by the literature [28] since the size of the abrasive particles is a significant factor in surface integrity rather than other parameters. Nevertheless, no surface discontinuities were apparent; center-injected polishing was comparable with conventional polishing.

4.2 Material Removal Rate

Compared with conventional polishing, center-injected polishing exhibited much higher material removal rates (MRRs). Figure 6 compares the material removal depths according to slurry supply method in terms of the MRR (in units of removed depth per processing time). At the same rotational speed and flow rate, more slurry was introduced between the polishing pad and workpiece via center-injected polishing than via conventional polishing, thereby enhancing material removal.

During center-injected polishing, the material removal depth substantially increased as the rotational speed

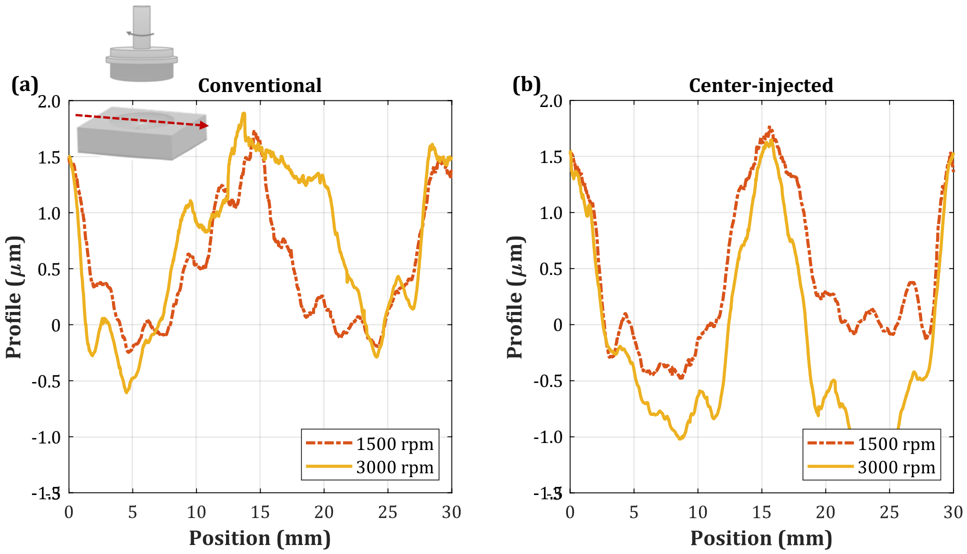


Fig. 3 Surface profiles after (**a**) conventional polishing and (**b**) center-injected polishing

Fig. 4 Experimental configuration of polishing system

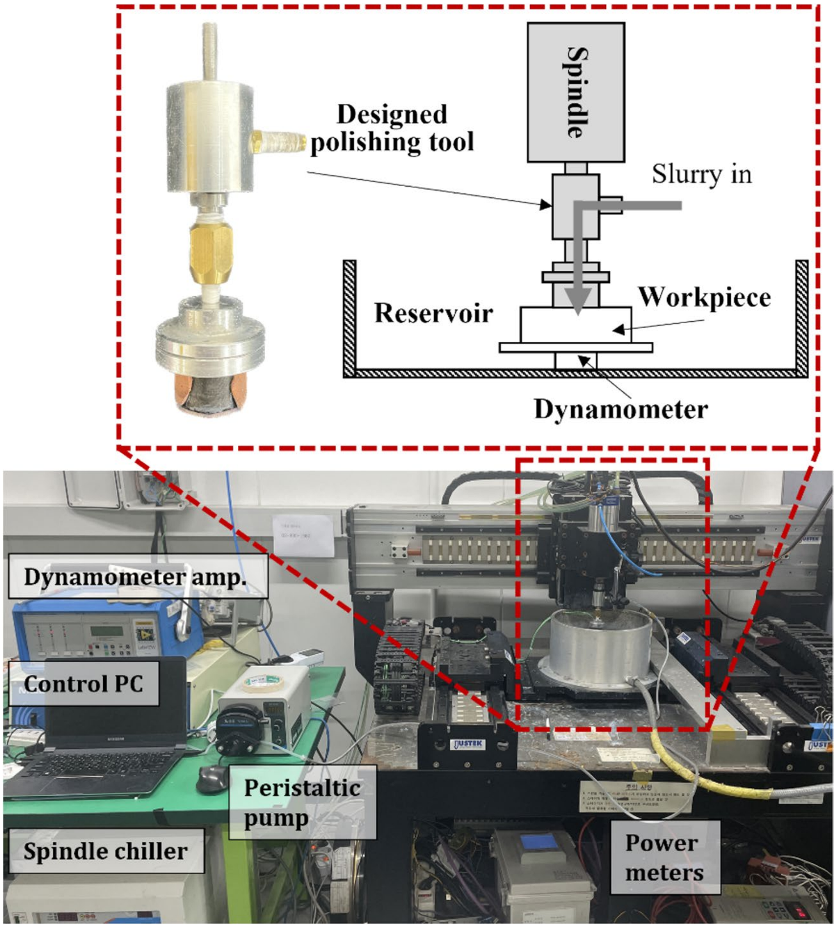
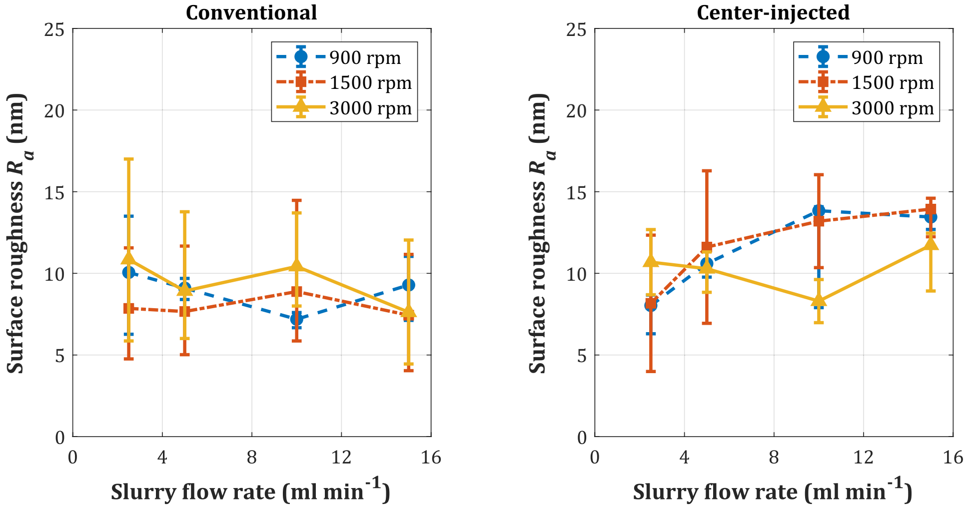


Table 1 Process parameters

Parameters	Values			
Rotational speed (rpm)	900	1,500	3,000	
Slurry flow rate (ml min^{-1})	2.5	5	10	15

increased. At higher rotational speeds, it was thought that more energy was transferred to the abrasives during the longer path length, thereby increasing the MRR. Slurry supply was sufficient at all rotational speeds; the MRR did not increase as the slurry flow rate increased. The result implies

Fig. 5 Polished surfaces and surface roughness (R_a) values after conventional polishing (left) and center-injected polishing (right)



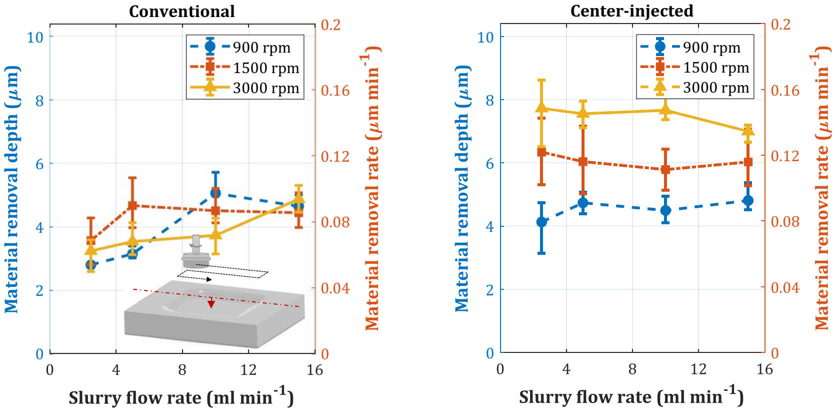


Fig. 6 Material removal depths of conventional polishing (left) and center-injected polishing (right)

that center-injected polishing could achieve the similar MRR even with a minimized slurry flow rate.

During conventional polishing, the MRR did not substantially vary according to rotational speed. Polishing at 3,000 rpm removed slightly less material, compared with polishing at 1,500 rpm. Rotational speeds do not significantly influence the slurry participation ratio. Unlike center-injected polishing, higher rotational speed hindered slurry supply more due to the centrifugal force. At 3,000 rpm, the MRR slightly increased as the slurry flow rate increased, suggesting that the slurry participation ratio slightly increased because more slurry reached the polishing area. The MRR may increase further as the slurry flow rate increases but is expected to converge at a certain flow rate, similar to the center-injected polishing. However, higher rotational speed is expected to require a higher slurry flow rate for convergence of MRR value.

When a specific removal depth is chosen, center-injected polishing utilizes slurry more efficiently without compromising surface quality. During conventional polishing, careful consideration of rotational speed and slurry flow rate are necessary; the experimental results indicate that center-injected polishing produces high MRRs regardless of slurry flow rate, even at the lowest tested rate.

4.3 Evaluation of Efficiency

To fully compare polishing efficiencies, the polished depth per unit of slurry volume was calculated as follows:

$$\text{Slurry efficiency}\left(\mu\text{m min}^{-1}\right) = \Delta h / \left(\dot{Q} \bullet \Delta t\right) \tag{1}$$

where Δh is the polished depth (μm), $\dot{Q}$ is the slurry supply rate (ml min^{-1}), and Δt is the processing time (min).

Figure 7 compares the slurry efficiencies of center-injected and conventional polishing. Compared with conventional polishing, center-injected polishing exhibited much higher slurry efficiency. A higher rotational speed led to greater slurry efficiency, as expected with the results in Sect. 4.2. More energy was expected to be transferred to the abrasives during the longer path length. Generally, slurry efficiency decreased as the slurry flow rate decreased; the increase in material removal depth was not proportional to the slurry flow rate.

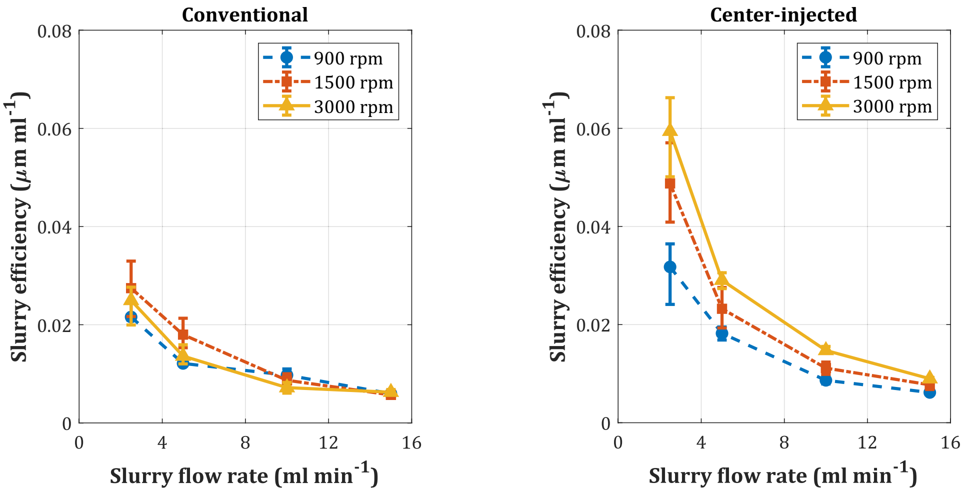


Fig. 7 Slurry efficiencies of conventional polishing (left) and center-injected polishing (right)

The specific energy consumptions (*i.e.*, energies consumed per removal of unit depth) were calculated by dividing the total energy consumption (E) by the removed depth (d) (volume).

$$\text{Specific energy consumption}\left(\text{kWh }\mu\text{m}^{-1}\right) = E/d \tag{2}$$

The energies consumed by the spindle, stage, and slurry pump were considered, but only the spindle exhibited substantial differences according to process parameters. The power consumptions of other components were similar. The spindle consumed slightly more power during center-injected polishing than during conventional polishing because more slurry was spread on the polishing pad; thus, rotation of the polishing pad required greater torque.

However, in terms of specific energy consumption, center-injected polishing was much more efficient than conventional polishing owing to higher MRRs (Fig. 8). During center-injected polishing, higher rotational speed showed less specific energy consumption, proving the high energy transfer and utilization in material removal. The slurry flow rate did not influence the specific energy consumption; it is thought that a similar amount of slurry was introduced between the pad and the workpiece regardless of the flow rate. During conventional polishing, the results imply that the energy transfer or utilization ratio did not vary with respect to rotational speeds, just like the MRR results. Increasing the flow rate did not influence the total energy consumption, but could lower the specific energy consumption, particularly at 900 rpm.

Considering the results, center-injected polishing reduced slurry consumption and increased process efficiency. Although the higher spindle speed consumed more power, the specific energy consumption was much lower during 3,000-rpm center-injected polishing because of the higher MRR.

4.4 Prediction of MRR Using the Extended Preston Equation

To predict polishing performance, the extended Preston equation was fitted to the experimental results, in accordance with the method of Luo et al. [29].

$$\text{MRR} = \left(C_1P + C_2\right)V + C_3 \tag{3}$$

where P is the polishing pressure; V is the relative velocity between the workpiece and polishing pad; and C_1, C_2, and C_3 are empirical constants. Following the work done by Luo et al. [29], three-body rolling is expected to be predominant at specific values of P and V; friction coefficients may change according to changes in processing parameters. Both P and V were considered in the MRR calculation.

Figure 9 shows the regression model predicting the MRR (red dotted line) and the experimental results at

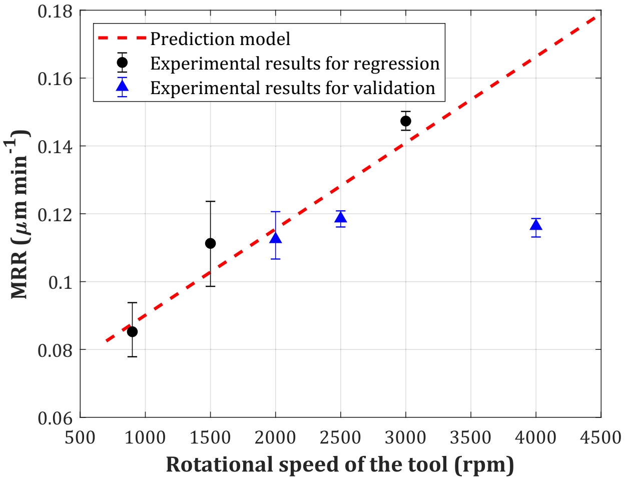
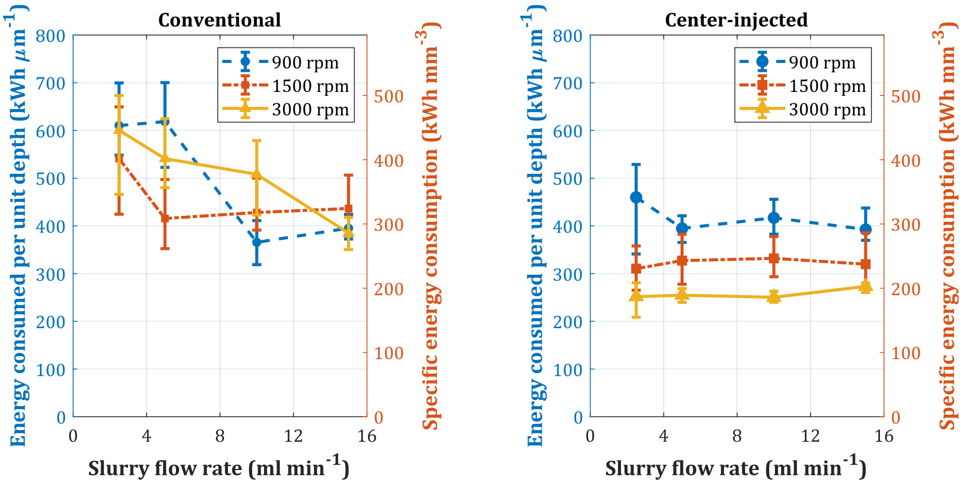


Fig. 9 Predictive model of MRR using extended Preston equation

Fig. 8 Specific energy consumption during conventional polishing (left) and center-injected polishing (right)



rotational speeds of 2,000, 2,500, and 4,000 rpm (blue triangles) to check the developed process maintains the same process mechanisms. Below 3,000 rpm, the regression model with the extended Preston equation adequately predicted the MRR. The MRR drastically decreased when the rotational speed exceeded 4,000 rpm, presumably because of slurry starvation; the slurry was centrifugally spun away at high rotational speeds. Thus, the dominant interactions of abrasives and the workpiece might vary and the coefficients in Eq. (3) were not predictive in this region. It is thought that the critical rotational speed limit would exist between 3,000 and 4,000 rpm, and further experiments can identify the limit for more detailed process modeling. However, the MRR was adequately predicted by the extended Preston equation when the slurry supply was sufficient.

The process capability of center-injected polishing is shown in Fig. 10. The MRR is approximately twice the rate achieved by conventional polishing at the same processing conditions, and the slurry consumption is reduced by about 60% at the same MRR. In center-injected polishing, MRR increases as the rotational speed increases, but it requires a bit more slurry consumption owing to higher centrifugal force. Increased polishing pressures showed increased MRRs in other experimental sets, but its effect on slurry consumption requires more in-depth analysis. The optical image shows that a finely finished surface could be achieved via center-injected polishing, with considerably less slurry consumption. Because surface roughness values were similar regardless of the slurry supply method, it was concluded that center-injected polishing reduces slurry consumption and improves process efficiency without compromising surface quality. Throughout the efforts in efficient slurry supply, it is expected that this research can facilitate environmentally benign and sustainable polishing processes.

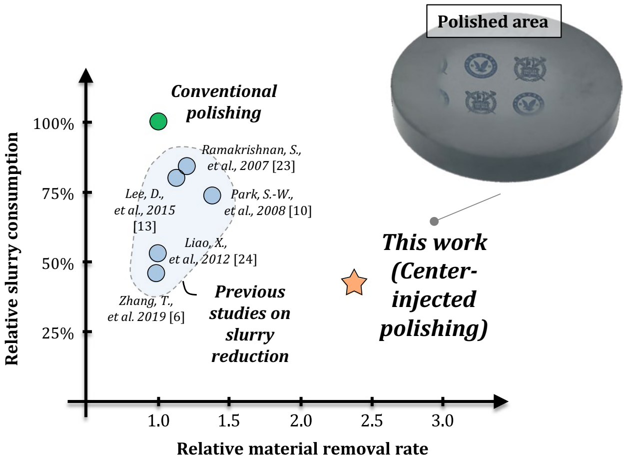


Fig. 10 Process capability of the novel center-injected polishing method and optical image of a perfectly polished surface

5 Conclusion

A center-injected polishing system was developed to efficiently deliver slurry between the polishing pad and workpiece, thereby improving process efficiency. Slurry delivery to the center of the polishing pad improves the slurry utilization ratio, reducing both slurry and specific energy consumption. Center-injected polishing maintains process throughput regardless of slurry flow rate, and even shows the highest efficiencies at the lowest tested slurry flow rate. The extended Preston equation well predicted the MRR up to a certain rotational speed value. Compared to conventional polishing, center-injected polishing could increase the material removal rate more than two times at the same slurry supply condition or achieve the same material removal rate with 60% reduced slurry consumption.

Here, the slurry was injected into the empty space of the center of the pad. Further investigations will be conducted to find out an efficient delivery of slurry to the slurry film between the pad and the workpiece. More detailed investigation of the effects of the slurry film thickness to predict the process performance at a wider rotational speed range, as well as identifying critical speed limit. The developed method will also be implemented in freeform surface polishing. The center-injection method will be applied to tilted polishing tools, with analyses of slurry flow. It is expected that efficient slurry utilization will reduce the environmental footprint of abrasive processes.

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Declarations

Conflict of Interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Hashimoto, F., Yamaguchi, H., Krajnik, P., Wegener, K., Chaudhari, R., Hoffmesiter, H.-W., & Kuster, F. (2016). Abrasive fine-finishing technology. *CIRP Annals, 65*(2), 597–620. https://doi.org/10.1016/j.cirp.2016.06.003
2. Yu, T., Zhang, T., Yu, X., Yang, X., & Sun, J. (2019). Study on optimization of ultrasonic-vibration-assisted polishing process parameters. *Measurement, 135*, 651–660. https://doi.org/10.1016/j.measurement.2018.12.008
3. Jung, H., Jeong, S., Park, Y., Shin, Y., & Jeong, H. (2023). X-ray diffraction analysis of damaged layer during polishing of silicon carbide. *International Journal of Precision Engineering and Manufacturing, 24*(1), 25–32. https://doi.org/10.1007/s12541-022-00711-5
4. Liu, C.-W., Chen, H.-C., & Lin, S.-C. (2023). Acoustic emission monitoring of grinding-polishing of extra-low dispersion lens. *International Journal of Precision Engineering and Manufacturing, 24*(1), 53–60. https://doi.org/10.1007/s12541-022-00733-z
5. Lee, H., Kim, H., & Jeong, H. (2022). Approaches to sustainability in chemical mechanical polishing (CMP): A review. *International Journal of Precision Engineering and Manufacturing-Green Technology, 9*(1), 349–367. https://doi.org/10.1007/s40684-021-00406-8
6. Zhang, T., Zhao, Y., Yu, T., Yu, T., Shi, J., & Zhao, J. (2019). Study on polishing slurry waste reduction in polishing monocrystalline silicon based on ultrasonic atomization. *Journal of Cleaner Production, 233*, 1–12. https://doi.org/10.1016/j.jclepro.2019.06.067
7. Won, J. J., Lee, Y. J., Hur, Y. J., Kim, S. W., & Yoon, H. S. (2023). Modeling and assessment of power consumption for green machining strategy. *International Journal of Precision Engineering and Manufacturing-Green Technology, 10*(3), 659–674. https://doi.org/10.1007/s40684-022-00455-7
8. Yang, G., He, P., & Qu, X.-P. (2018). Inhibition effect of glycine on molybdenum corrosion during CMP in alkaline H2O2 based abrasive free slurry. *Applied Surface Science, 427*, 148–155. https://doi.org/10.1016/j.apsusc.2017.08.140
9. Yang, X., Yang, X., Kawai, K., Arima, K., & Yamamura, K. (2021). Novel SiC wafer manufacturing process employing three-step slurryless electrochemical mechanical polishing. *Journal of Manufacturing Processes, 70*, 350–360. https://doi.org/10.1016/j.jmapro.2021.08.059
10. Park, S.-W., Seo, Y.-J., & Lee, W.-S. (2008). A study on the chemical mechanical polishing of oxide film using a zirconia (ZrO2) – mixed abrasive slurry (MAS). *Microelectronic Engineering, 85*(4), 682–688. https://doi.org/10.1016/j.mee.2007.12.049
11. Wang, Z., Ding, Y., Wang, P., Pang, M., Zhao, H., Ma, L., Nie, F., & Su, J. (2023). Research of dry tribochemical mechanical polishing SiC with an innovation abrasive-catalytic abrasive cluster. *The International Journal of Advanced Manufacturing Technology*. https://doi.org/10.1007/s00170-023-11613-9
12. Poudel, B., Lee, P. H., Song, G., Nguyen, H., Kim, K., Jung, K., Shao, C., Kwon, P., & Chung, H. (2022). Innovative magnetic-field assisted finishing (MAF) Using nano-scale solid lubricant: A case study on mold steel. *International Journal of Precision Engineering and Manufacturing-Green Technology, 9*(6), 1411–1426. https://doi.org/10.1007/s40684-021-00404-w
13. Lee, D., Lee, H., & Jeong, H. (2015). The effects of a spray slurry nozzle on copper CMP for reduction in slurry consumption". *Journal of Mechanical Science and Technology, 29*(12), 5057–5062. https://doi.org/10.1007/s12206-015-1101-2
14. Lee, H., & Jeong, H. (2015). Analysis of removal mechanism on oxide CMP using mixed abrasive slurry. *International Journal of Precision Engineering and Manufacturing, 16*(3), 603–607. https://doi.org/10.1007/s12541-015-0081-6
15. Lee, H. S., Kim, D. I., An, J. H., Lee, H. J., Kim, K. H., & Jeong, H. (2010). Hybrid polishing mechanism of single crystal SiC using mixed abrasive slurry (MAS). *CIRP Annals, 59*(1), 333–336. https://doi.org/10.1016/j.cirp.2010.03.114
16. Suzuki, H., Okada, M., Namba, Y., & Goto, T. (2019). Superfinishing of polycrystalline YAG ceramic by nanodiamond slurry. *CIRP Annals, 68*(1), 361–364. https://doi.org/10.1016/j.cirp.2019.04.062
17. Lauwers, B., Klocke, F., Klink, A., Tekkaya, A. E., Neugebauer, R., & Mcnitosh, D. (2014). Hybrid processes in manufacturing. *CIRP Annals, 63*(2), 561–583. https://doi.org/10.1016/j.cirp.2014.05.003
18. Rech, J., Krzak, D., Roy, F., Salvatore, F., Gidon, A., & Guérin, S. (2022). A new hybrid electrochemical-mechanical process (PEMEC) for polishing complex and rough parts. *CIRP Annals, 71*(1), 173–176. https://doi.org/10.1016/j.cirp.2022.03.011
19. Gao, X., Li, X., He, Y., Fan, L., & Tang, M. (2022). Investigation on electrical enhanced photocatalysis polishing of single-crystal silicon carbide substrates. *International Journal of Precision Engineering and Manufacturing, 23*(11), 1261–1274. https://doi.org/10.1007/s12541-022-00708-0
20. Lee, H., Kim, M., & Jeong, H. (2015). Effect of non-spherical colloidal silica particles on removal rate in oxide CMP. *International Journal of Precision Engineering and Manufacturing, 16*(13), 2611–2616. https://doi.org/10.1007/s12541-015-0334-4
21. Lee, H., Lee, D., Kim, M., & Jeong, H. (2017). Effect of mixing ratio of non-spherical particles in colloidal silica slurry on oxide CMP. *International Journal of Precision and Engineering and Manufacturing, 18*(10), 1333–1338. https://doi.org/10.1007/s12541-017-0158-5
22. Tan, Y., Ni, Y., Wu, J., Li, L., & Tan, D. (2023). Machinability evolution of gas-liquid-solid three-phase rotary abrasive flow finishing. *The International Journal of Advanced Manufacturing Technology*. https://doi.org/10.1007/s00170-022-10761-8
23. Ramakrishnan, S., Janjam, S., Patri, U., Roy, D., & Babu, S. (2007). Comparison of dicarboxylic acids as complexing agents for abrasive free chemical mechanical planarization of copper. *Microelectronic engineering, 84*(1), 80–86. https://doi.org/10.1016/j.mee.2006.08.011
24. Liao, S., Sampurno, Y., Zhuang, Y., & Philipossian, A. (2012). Effect of slurry application/injection schemes on slurry availability during chemical mechanical planarization (CMP). *Electrochemical and Solid State Letters, 15*(4), H118. https://doi.org/10.1149/2.009205esl
25. Lin, B., Jiang, X.-M., Cao, Z.-C., & Li, Y. (2018). Novel disc hydrodynamic polishing process and tool for high-efficiency polishing of ultra-smooth surfaces. *Micromachines, 9*(7), 333. https://doi.org/10.3390/mi9070333
26. Kusumi, T., Sato, Y., Akagami, Y., & Umehara, N. (2011). New polishing method using water-based slurry under AC electric field for glass substrate. *Journal of magnetism and magnetic materials, 323*(10), 1394–1397. https://doi.org/10.1016/j.jmmm.2010.11.053
27. Kim, M., Bang, S., Kim, D. H., Lee, H. T., Kim, G. H., & Ahn, S. H. (2020). Hybrid CO_2 laser-polishing process for improving material removal of silicon carbide. *The International Journal of Advanced Manufacturing Technology, 106*, 3139–3151. https://doi.org/10.1007/s00170-019-04846-0
28. Xie, Y., & Bhushan, B. (1996). Effects of particle size, polishing pad and contact pressure in free abrasive polishing. *Wear, 200*(1–2), 281–295. https://doi.org/10.1016/S0043-1648(96)07275-4
29. Luo, Q., Ramarajan, S., & Babu, S. (1998). Modification of the Preston equation for the chemical-mechanical polishing of copper. *Thin Solid Films, 335*(1–2), 160–167. https://doi.org/10.1016/S0040-6090(98)00896-7

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