PCD for Consumer Electronics Machining

Ceramic machining manufacturers face relentless pressures to improve productivity and surface quality while cutting costs, especially in volume-applications such as consumer electronics (CE). Tools with nickel electroplating (EP) were traditionally adopted to machine CE devices such as watches and smartphones. However, EP tools present significant drawbacks, including limited durability and environmental harm. More brittle materials, such as engineered glass, zirconia, sapphire, and onyx are now being incorporated in smart devices, making traditional EP tooling less adequate to meet CE's demanding needs.

PCD offers 70 times longer tool life and 4 times improved surface roughness than traditional EP tools

Leveraging over 70 years of expertise and innovation, Element Six (E6) have collaborated with a leading Chinese CE manufacturer to test its PCD tools in peripheral milling operations for smartphones glass. Results showed enhanced durability, extended tool life, and improved finish, compared to conventional EP tools. Customized tool design and operating conditions eliminated the need for polishing processes, typically linked to sub-surface damage caused by the tool.

The challenge
To achieve the combination of smooth surface and strength, the workpiece surface finish and residual stress must be carefully controlled. Thus, machining in the ductile regime, characterized by plastic deformity, is needed to avoid micro-crack formation and stresses.
The undeformed chip thickness (h_m, shown in Figure 1) is the most critical parameter to characterize the ductile regime [Bifano et al. (1991), Marshall et al. (1982)]. Typically, h_m is affected by several parameters, including the mechanical properties of workpiece material, tool design and operating conditions. The ductile mode is defined when h_m is smaller than the brittle-to-ductile transition chip thickness (DBh_m) of the workpiece material [Bifano et al. (1991)].

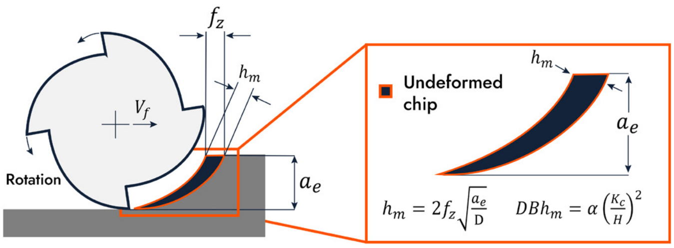


Figure 1. Definition of h_m and DBh_m. Ductile mode occurs when $h_m < DBh_m$.

Micro-milling tools
E6 provides synthetic diamond tooling solutions to meet these challenges. Unlike a traditional trial-and-error approach, E6's tool design is based on phenomenological models that consider all critical performance indicators required for the tool to perform well.

In addition to the tool design, fabrication techniques of micro-milling tools have improved, and precise and geometrically complex features in tooling are becoming increasingly less challenging. Laser finishing is an enabling technology that can be used to fabricate the highly intricate tool geometries required for micro-machining tools used for brittle material machining. Nanosecond lasers are typically used in manufacturing since they are stable, reliable, and cost-effective.

Internal testing - Element Six's Global Innovation Center
Ductile-brittle transition assessment:
Initial tests were conducted with a commercially available 3-axis machining center (HURCO VM20i) to estimate the DBh_m for Gorilla® glass in a peripheral milling operation using E6's CTM302 PCD micro-milling tool. Based on the performance and productivity requirements, the PCD micro-milling tool was designed with 3 tiers and 50 flutes (Figure 2).

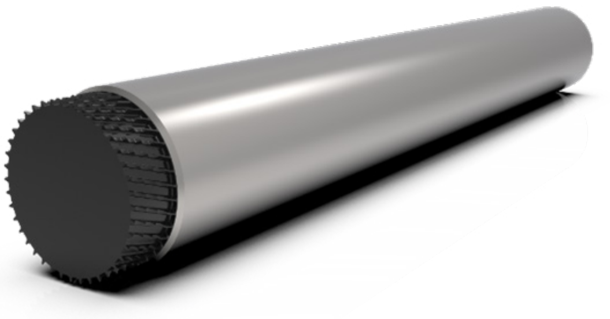


Figure 2. PCD tool design for peripheral milling operation with 3-tier and 50 flutes.

The Gorilla® glass surface roughness (Sa) analysis was acquired during the experiments using an Alicona COBOT optical roughness measurement system. Figure 3 shows the experimental setup.

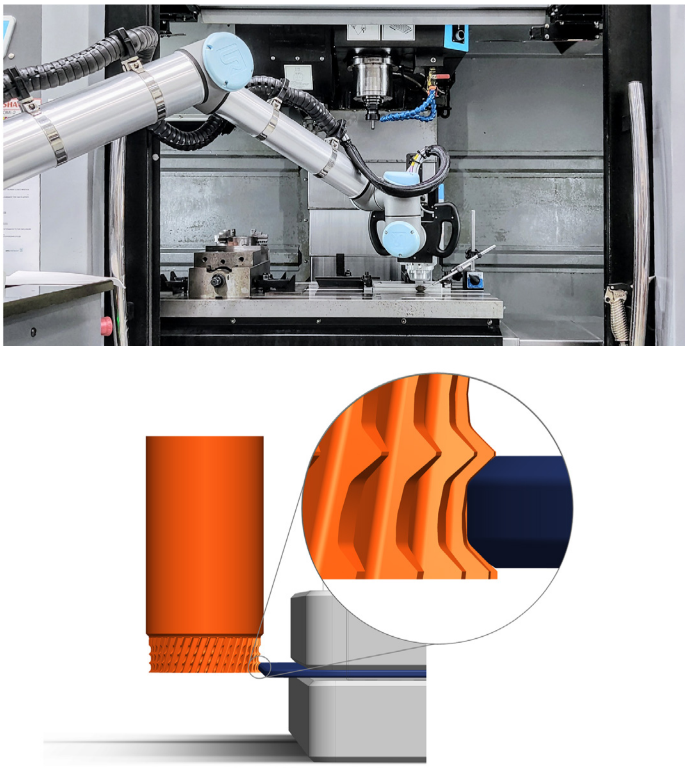


Figure 3. Test setup and a sketch of the milling operation process.

Figure 4a shows the Sa versus h_m diagram for peripheral milling operation machining conducted with the micro-milling PCD tool. The diagram reveals that Sa increases with h_m, and the ductile regime is achieved for $h_m < 0.012$ µm, as indicated in the SEM images (Figure 4b). It is worthwhile to highlight that the Sa value obtained for h_m = 0.012 μm delivers a similar quality as a polished surface obtained during the post-machining polishing step (S_a < 100 nm), suggesting that micro-milling tools with appropriate design and operating conditions can potentially eliminate this requirement.

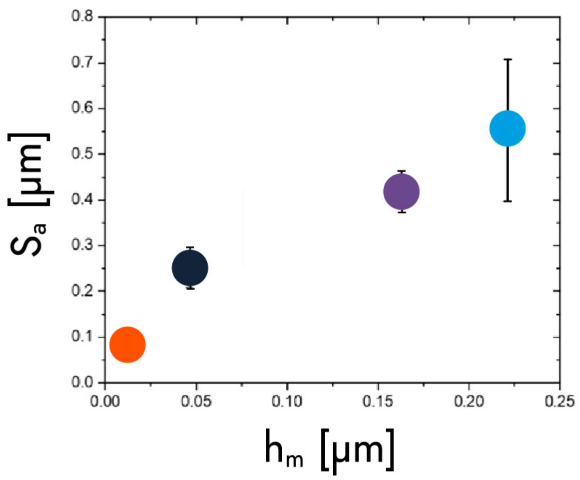


Figure 4a. Surface roughness (S_a) vs underformed chip thickness (h_m).

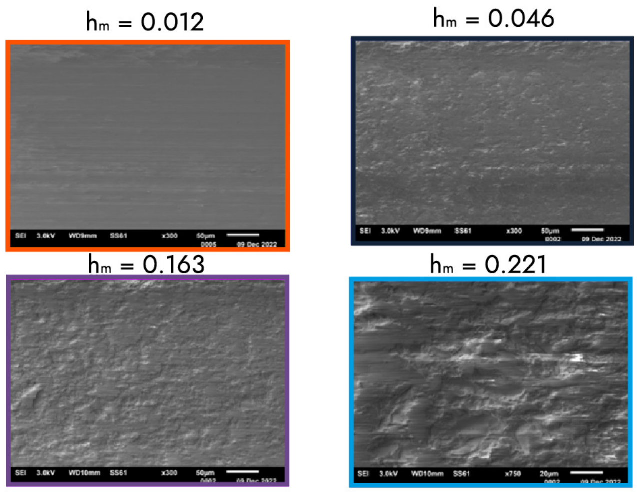


Figure 4b. SEM images of surface finish.

Production Testing in China

The lessons learned from the internal testing were used to refine and improve the PCD tool used in the production environment in China. Considering the optimal values for h_m determined at the E6 Global Innovation Center, the PCD micro-milling tool also showed an exceptional surface finish quality (S_a< 90 nm) at least 4 times superior to the surface machined with the EP tool EP tool (see Table 1).

Table 1. Surface roughness Sa for PCD vs EP.

PCD	EP (existing solution)
86.9 +/- 10.9 nm	413.1 +/- 48.4 nm

Tool Lifetime

The tool life of the PCD micro-milling compared to the conventional EP tool was also investigated. The operating conditions used for the PCD micro-milling tool were: Feed = 70 mm/min, Rotary speed = 24000 RPM, Depth of cut (a_e) = 0.01 mm (i.e., h_m = 5 nm). The typical EP tool life is 150 pieces, considering a limit value for S_a ≈ 400 nm. Using the same life criteria (S_a ≈ 400 nm), the PCD tool's life is ≈ 3500 pieces/tier, or > 10,000 for all 3 tiers, i.e., ≈ 70 times more than the conventional EP tool.

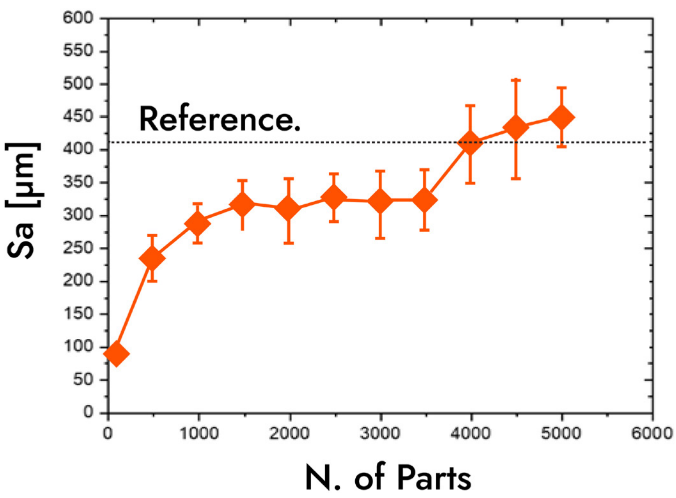


Figure 5. Tool life of the PCD micro-milling tool for Gorilla® glass peripheral milling operation.

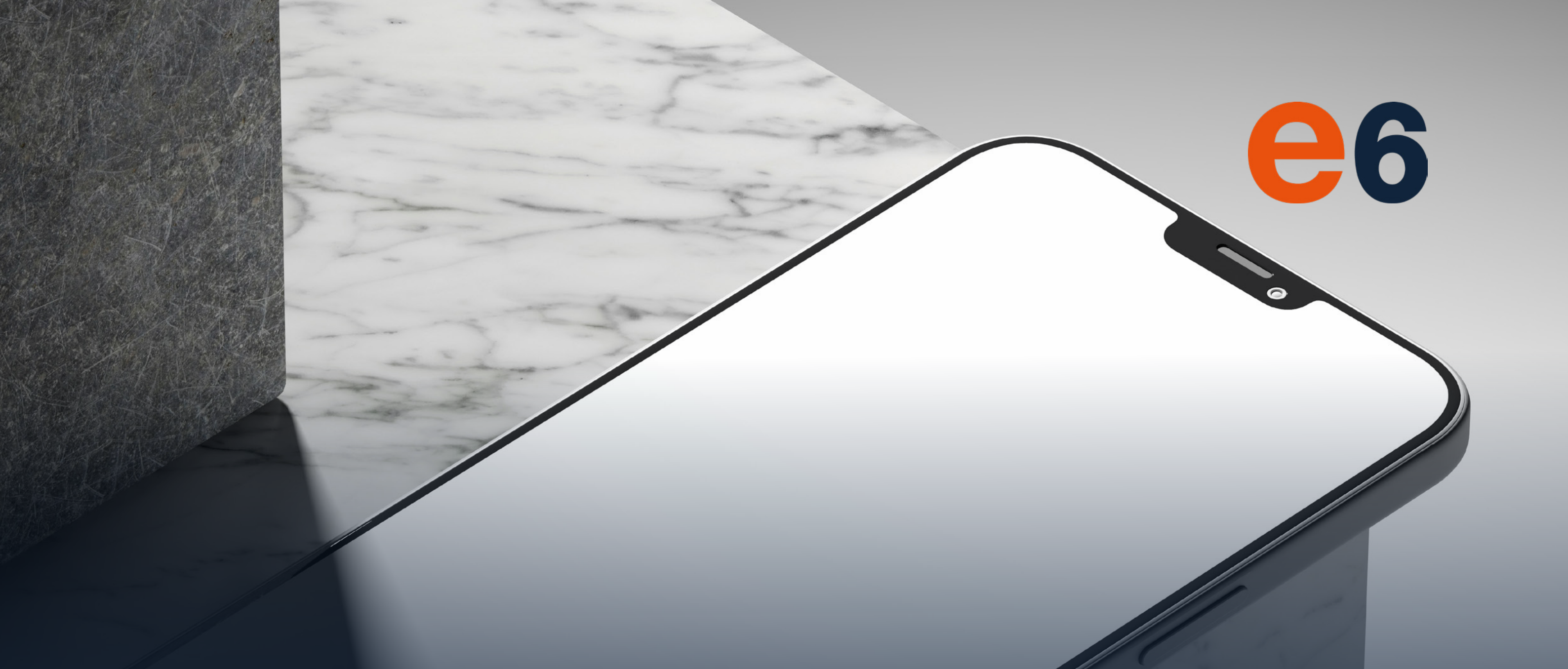
Tooling Economics

The Table 2 summarizes some of the economical aspects of the two different milling tool types.

Table 2. Cost per part for both EP and PCD tool.

Tool Type	N. of tools	Tool cost/part	Comments
EP	150	$ 0.05	Frequent tool changes reduce productivity
PCD	10,500	$ 0.04	Potential to eliminate the final polishing step

Note that the tool cost per workpiece is slightly lower for the PCD tool. The EP tools have an additional disadvantage of requiring frequent tool changes and thus decreasing overall equipment effectiveness (OEE) with tool-change time. The PCD micro-milling tools have the potential significant additional advantage of eliminating the polishing step, thereby substantially lowering the overall manufacturing cost per part.



E6’s PCD solutions deliver 70 times longer tool life and 4 times improved finish compared to EP tools

Conclusions

E6 provides synthetic diamond tooling solutions to meet these challenges. This case study showed that defined cutting-edge PCD tools perform more effectively than EP tools. With careful tool design and control of machining operating parameters, PCD can achieve surface roughness $S_a \leq 100$ nm, demonstrating a 4-fold improvement to EP tools. Using a 3-tier tool design, PCD micro-milling tools can obtain lifetimes of 70 times longer than EP tools, resulting in less tool cost per part and far less OEE. In addition, defined PCD tools are able to replace the subsequent polishing process required to eliminate the sub-surface damage caused by the EP tools. With decades of experience in diamond synthesis, E6 is uniquely positioned to enable the adoption of PCD tools for ceramic milling applications for high-volume CE components.

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About Element Six

Element Six is a global leader in the design, development and production of synthetic diamond and tungsten carbide advanced material solutions. Part of the De Beers Group, our primary manufacturing sites are located in the US, UK, Germany, Ireland, and South Africa.

Since 1946, our focus has been on developing the synthesis processes to enable innovative synthetic diamond and tungsten carbide solutions. As well as being the planet’s hardest material, diamond’s extreme and diverse properties give it high tensile strength, chemical inertness, broad optical transmission and very high thermal conductivity.

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