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Surface integrity of fluid jet polished tungsten carbide

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Abstract

In recent years, Fluid Jet Polishing (FJP) has been studied for its potential as a finishing method on optical lenses, mirrors and molds for a number of materials, such a glass and nickel. In this paper, the surface integrity of binderless tungsten carbide after polishing by FJP was studied experimentally. Two aspects in particular were focused on: (1) identifying process conditions under which grain boundaries may dislocate (thus leading to unintentional loss of grains from the substrate) and (2) identify process conditions under which abrasive particles may become embedded into the substrate, in order to prevent surface contamination.

Keywords: Carbide; Fluid Jet Polishing, Surface Integrity

1. Introduction

The fabrication of optical components to ultra-precision criteria (understood here as form error less than 100 nm P-V and surface roughness less than 2 nm Ra) generally involves a number of processing steps such as milling, precision grinding, polishing, and some final finishing process.

In recent years, Fluid Jet Polishing (FJP) has been studied for its potential as a finishing method for complex optical lenses, mirrors and molds on a number of materials from glass to nickel [1,2]. Some advantages of this process include the ability to generate sub-millimeter polishing footprints, a wide range of material removal rates through variation of the abrasive grit size and inlet pressure, a propensity for removing machining marks from prior processes without introducing another tool signature, as well as the absence of tool wear.

In the FJP process, a mixture of water and abrasive particles is delivered by a pump to a converging nozzle of outlet diameter usually between 0.1 and 2.0 mm. The jet impinges the workpiece, thus generating a polishing spot. The spot is then moved along a tool path with tight track spacing, which allows overlapping of the spot over several tracks. The typical pressure range for the slurry inlet is between 1 and 20 bar, while abrasive grit size may range from 0.1 to 50 µm. Empirical studies have shown that FJP typically delivers a surface finish that is a factor of inlet pressure, material type, abrasive type and grit size [2,3].

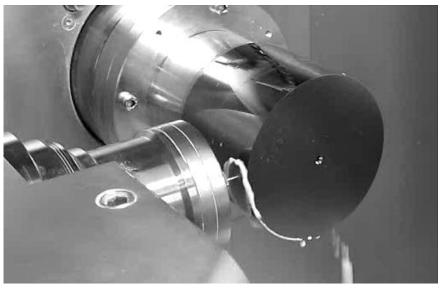

Fig. 1. Fluid jet polishing of mandrel for X-ray mirror replication [2].

Some desirable surface altering properties of FJP have been documented in previous studies, such as a propensity for removing diamond turning marks on soft

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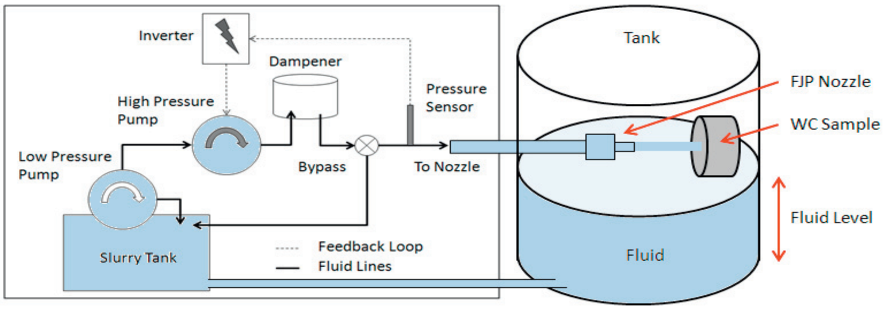


Fig. 2. Fluid Jet Polishing experimental setup, using a tank with variable fluid level.

metals such as Nickel [4]. But some detrimental effects have also been observed. A study by Grant et al. using electron microscopy showed that FJP can cause brittle fracture and pluck-out of grains when processing tungsten carbide material [5]. Another study by Tsai et al. reported embedding of abrasive particles into steel molds produced by electro-discharge machining [6].

In this paper, the surface integrity of binderless tungsten carbide (WC) polished by FJP was studied experimentally. Two key aspects were focused on: (1) clearly identify and avoid process conditions under which grain boundaries may dislocate (thus leading to unintentional loss of grains from the substrate), and (2) identify and avoid process conditions under which abrasive particles may become embedded into the substrate, in order to prevent surface contamination.

2. Experimental Procedure

2.1. Experimental Setup

For the FJP experiments, a 0.8 mm diameter sapphire nozzle (produced by laser drilling) was pointed with normal incidence to the workpiece, at a stand-off distance of 2.0 mm. In contrast to previous experiments, in this study the nozzle was located inside a tank. It could thus be operated in two different modes: either completely submerged under the polishing fluid, or propagating through air (see Fig. 2, right). In order to improve inlet pressure stability, a low pressure feed-in pump was coupled with a high pressure pump inside the system (see Fig. 2, left), and the pressure gauge output-signal was interfaced to the inverter powering the pump [7]. A feedback control loop was thus established, which improved overall pressure stability and corrected the average pressure drift (see Fig. 3).

To further improve system performance, a bypass was also installed on the system, which allowed variations in fluid flow within the slurry delivery system for a given nozzle inlet pressure (in order to avoid resonant frequencies between the pulsating pump and overall system).

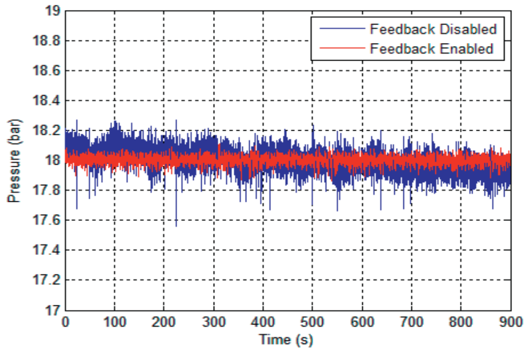


Fig. 3. Pressure stability with feedback loop disabled/enabled.

2.2. Workpiece Material

For this series of experiments, binderless tungsten carbide of grain size 0.6 μm was pre-machined by micro-grinding, using a small polycrystalline diamond wheel (ground surface texture was around 4~5 nm Ra).

Carbides of silicon (SiC), titanium (TiC) and tungsten (WC) are widely used in the manufacture of precision molding dies. In the early days, WC, TiC or SiC were mixed with cement in the form of Co, Fe or Ni. WC was also usually mixed with other carbides, as it is difficult to sinter by conventional hot pressed sintering technique [8]. Provided that the carbide material was not introduced to environments that enhance corrosion in the non-ferrous binding material, the performance of such cemented carbide was effective. Later developments have enabled the production of cement-less carbides, free from any metal binder, in order to enhance performance in harsh environments. Fully binderless manufacturing processes include spark plasma sintering [9] and microwave radiation [10].

But it is important to note that while binderless carbides prevent the adverse effects of corrosion, this comes at a cost: although hardness is similar or slightly higher, the fracture toughness of binderless carbide is actually lower than cemented carbide. The result is reduced wear resistance, and shorter lifetime in industrial applications (before replication tolerances are breached).

2.3. Experimental Parameters

The FJP experimental parameters are summarized in Table 1. The first set of experiments consisted of checking the difference between submerged and non-submerged condition of the nozzle, using only pure water (no abrasive particles). The range of inlet pressures spanned from 2 and 18 bar. For each pressure, the nozzle was pointed at a different location of the workpiece and allowed to dwell for 15 min. Afterwards, these locations were observed with both optical and confocal laser microscopes.

The second set of experiments consisted of checking the propensity for abrasive particles to stick to the surface after polishing by FJP (in the submerged condition). Alumina grit between #10,000 and #700 (nominal size between 0.6 and 18 µm) was used, with inlet pressure between 2 and 16 bar. The experiments were then observed by confocal laser microscope.

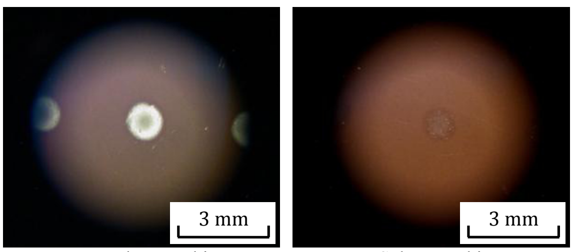
Table 1. Experimental parameters

Workpiece	Binderless WC
Grain Size	0.6 µm
Nozzle	Sapphire insert
Diameter	0.8 mm
Distance	2.0 mm
Pressure	2 to 18 bar
Dwell Time	15 min
Abrasives	Alumina (Al_2O_3)
Grain Size	0.6 to 18 µm
Concentration	0 to 40 g/L

3. Results and Discussion

3.1. Grain Boundary Effects

For the non-submerged water jetting experiments, it was found that the surface became significantly granular and whitened for inlet pressures above 4 bar. The whitening was linked to light scattering resulting from degradation in the surface texture (see Fig 4, left).

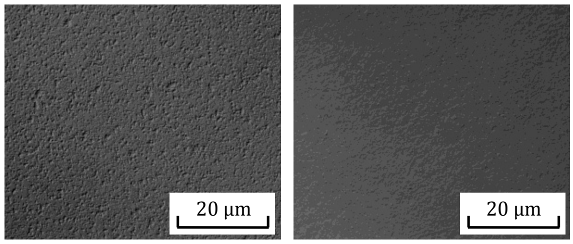


Non-submerged jet Submerged jet

Fig. 4. Optical microscope observations of water jetting experiments.

This phenomenon could not be observed in any of the submerged water jetting experiments (see Fig 4 right), the only visible effect being a slight darkening of the surface, most likely due to removal of a very thin oxide layer on the WC surface [11].

To better understand this phenomenon, the samples were observed at higher magnification (100x) with a laser confocal microscope. By comparing the dimension of surface features against the lateral scale, it was determined that grain boundaries were dislocating on the surface of the non-submerged water jetted samples, resulting in a progressive loss of grains from the bulk material (see Fig. 5, left). Such fracturing was not visible for the submerged nozzle experiments (see Fig. 5, right).



Non-submerged jet Submerged jet

Fig. 5. Laser microscope observations after water jetting experiments.

Since the difference in surface condition after non-submerged and submerged water jetting was consistent for a wide range of inlet pressures, it is unlikely that this phenomenon is related to the impact velocity of the jet stream (which, for a given inlet pressure, should be slightly slower in the case of submerged jet). To verify this assumption, the fluid velocity at impact zone was computed numerically using the Computational Fluid Dynamics (CFD) module in the Finite Element Modeling (FEM) software COMSOL. Figure 6 shows the resulting fluid impact velocity magnitude as a function of nozzle inlet pressure, for both submerged and non-submerged conditions.

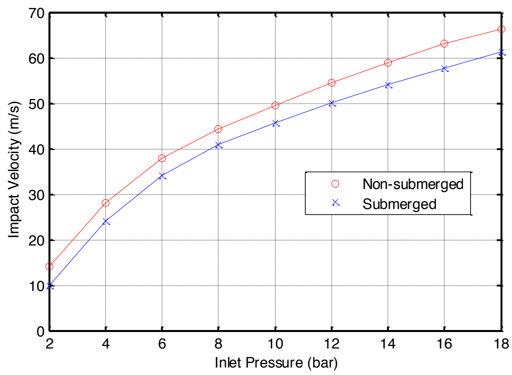


Fig. 6. CFD simulations of impact velocity magnitude as function of inlet pressure for “non-submerged” and “submerged” conditions.

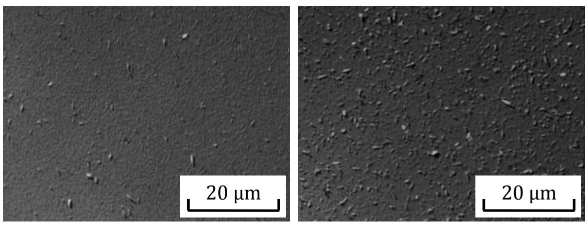
Because of the relatively small gap between nozzle and workpiece, the difference in velocity magnitude between the two conditions is very small. This leads to the conclusion that the dislocation phenomenon must be related to the propagation characteristics of the liquid jet through different mediums (air vs. water), rather than the small difference in impact velocity magnitude.

The experimental setup used sapphire nozzle inserts, which produce a smooth and glass-like jet under the given operating conditions. Cavitation forms at the sharp edges of the nozzle's orifice and is transported downstream. If the operating pressure is high enough, cavitation reaches the other side of the orifice and the jet no longer contacts walls, apart from the upstream edge. This condition is known as "hydraulic flip" and is described in [12]. In this condition, primary breakup by Plateau-Rayleigh instability is suppressed. The geometry of the upstream edge of the orifice directly influences the forming of cavitation and therefore requires high precision manufacturing, for instance by laser drilling.

But studies have shown that even such jets are not entirely free from break-up. Tafreshi et al [13] have observed that hydraulic flip water jets are affected by wind-induced breakup (an additional breakup mode to Ohnesorge's classification). It is thus possible that wind-induced breakup of the non-submerged fluid jet may cause turbulent oscillations of the force applied onto the surface, with sufficient vibrational energy being transferred to dislocate grain boundaries across the tungsten carbide surface. Alternatively, it is also possible that traveling through a liquid medium causes the jet to spread, thus resulting in a reduction of the kinetic energy per unit of volume, and distribution over a larger area.

3.2. Particle Embedding

Building on the results from the first set of experiments, the particle embedding trials were realized in the "submerged" condition. It was found that under certain process parameters abrasive particles can become embedded into the tungsten carbide surface after polishing by FJP (see Fig 7). When such embedding occurred it was sometimes very difficult to remove the particles, even using ultra-sonic vibration assisted cleaning equipment with various solvents.



2 µm alumina (8 bar) 2 µm alumina (16 bar)

Fig. 7. Laser microscope observations of embedded particles after FJP.

The occurrence of surface contamination was found to be a factor of both particle size and inlet pressure. Figure 8 shows the series of experimental data points as function of abrasive size and inlet pressure, and separates the areas for which embedding could be observed or not. From this diagram, it thus seems preferable to use FJP with large particles at low pressures, rather than fine abrasive at high pressures, in order to avoid particle embedding.

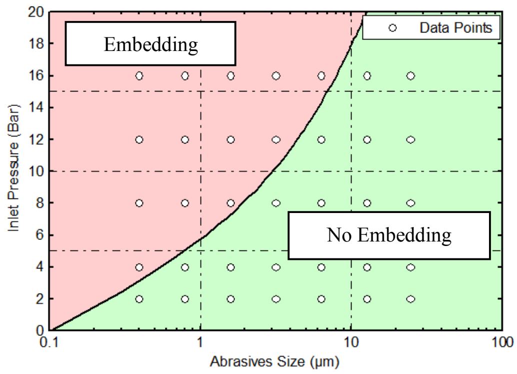


Fig. 8. Process conditions for which particle embedding was observed.

In order to find the cause of this phenomenon, finite element simulations of abrasive particle impacts were computed using the COMSOL multi-physics software. Using spherical approximation of the abrasive particles, it was found that peak contact pressure is a function of the nozzle inlet pressure, but independent of particle size (see Fig. 9, bottom). Meanwhile, the displacement and area of contact between the particle and surface (due to elastic deformation) were found to vary both with particle size and inlet pressure (see Fig. 9, top).

The ratio of peak contact area to particle weight was then calculated as a function of particle size, and the results shown in Fig. 10 (for inlet pressure of 8 bar). Across a particle size range of 0.5 and 8.0 µm, this ratio decreases by two orders of magnitude.

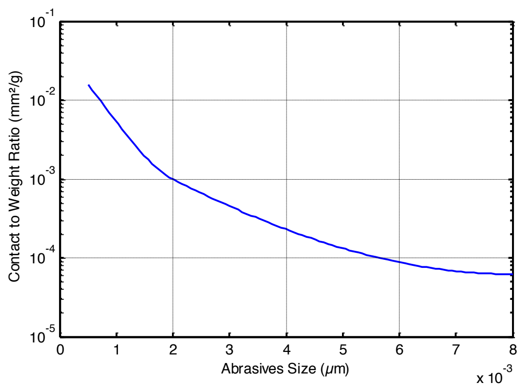


Fig. 10. Contact to weight ratio as a function of abrasive size (8 bar).

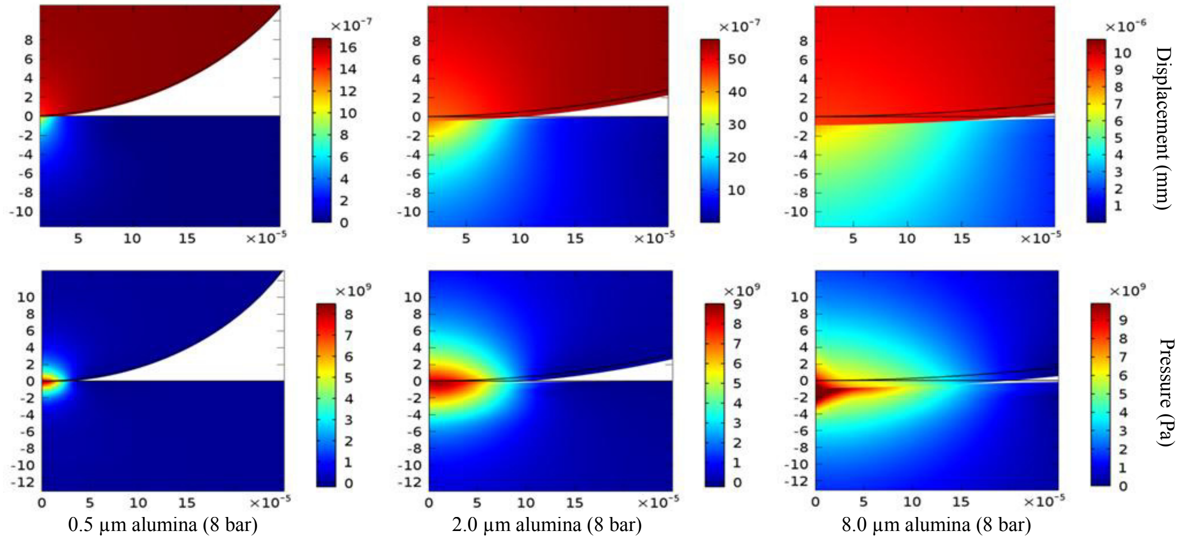


Fig. 9. Finite element simulations of abrasive particle impacts on tungsten carbide surface: peak displacement (top) and pressure (bottom)

By referring to the Johnson-Kendall-Roberts (JKR) model of elastic contact [14], it is possible to deduce from this result that for any given nozzle inlet pressure, the ratio of lost surface energy to stored elastic energy is greater for smaller particles. It can thus be inferred that a threshold value exists for which particles remain firmly adhered to the surface.

4. Conclusions

In several precision engineering sectors there is a continuing pressure to deliver superior surface quality. For example, quality specifications on molded aspheric lenses for mobile-phones are increasingly more stringent, as the number of detector-pixels increases. The work reported in this paper is therefore highly relevant in demonstrating a process-methodology that can deliver superior surface texture and integrity.

In this study, it was found that adverse phenomenon such as grain boundary dislocation (caused by wind-induced fluid breakup) and particle embedding (due to unreleased elastic contact) can adversely affect the integrity of fluid jet polished surfaces. However, the study has also uncovered practical guidelines to help ensuring that the surface integrity of binderless tungsten carbide does not become compromised after polishing by FJP:

1. Submerging the workpiece and nozzle inside the polishing fluid can prevent dislocation of the grain boundaries on the surface.
2. Using large abrasive grit size with low fluid pressure is preferable to the inverse, as it enables to achieve low surface texture [2] whilst avoiding contamination of the surface with embedded abrasive particles.

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