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A novel ultrasonic cavitation assisted fluid jet polishing system

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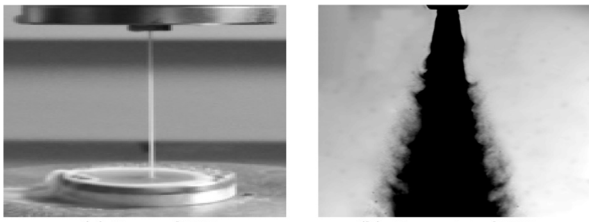
ABSTRACT

Fluid jet polishing is a versatile process used for super-fine finishing of small and complex optical and prosthetic surfaces. Advantages of this process include highly controllable sub-millimetre polishing footprints and absence of tool wear, though the main drawback is very low material removal rate. To address this issue, a novel system was developed in which ultrasonic cavitation causes micro-bubble generation directly upstream of the nozzle outlet. Experimental data shows that these micro-bubbles boost removal rate by up-to 380%, without causing any degradation of the surface finish. This paper reports on the modelling, implementation, and testing of this new polishing system.

1. Introduction

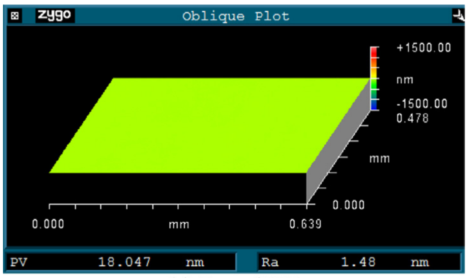
Fluid jet polishing (FJP) is a versatile process used in industry for super-fine finishing of small and complex components, in applications such as optics and medical surfaces [1,2]. Fig. 1a shows a photograph of the process: a slurry of water and abrasive particles is pressurized (0.2–2.0 MPa) and delivered through a nozzle of small outlet diameter (0.1–2.0 mm). The jet impinges the workpiece, generating a small polishing area. Some important advantages of this process include: (1) ability to generate sub-millimetre polishing footprints, (2) ability to reach difficult areas such as corners and cavities, and finally (3) absence of tool wear.

However, the main drawback of this process is its low removal rate (usually well below 1 mm^3/min). There exists a correlation between pressure and grit size on the one hand and material removal rate on the other [2,3], but increasing these factors tends to strongly degrade the surface integrity of polished parts [4]. To address this issue, various concepts have been proposed from employing magnetorheological fluid [5] to making arrays of jet nozzles [6]. The main line of research has concentrated on the idea of injecting air bubbles into the FJP slurry stream, before it exits from the nozzle. Messelink and Faehnle [7] first reported an experimental setup consisting of a pulsating air supply and mixing valve. In another attempt, Yu et al. [8] designed a nozzle inside which the Venturi effect is used to draw slurry into an air stream. In both cases, the mixing of slurry with large air bubbles was found to increase material removal rate significantly (more than 1000%). However, it also causes break-up of the jet plume, as shown in Fig. 1b. This results in a loss of process stability, and very poor surface finish. Using the setup proposed by Messelink, low pressure (0.4 MPa) polishing comparison trials between normal and air-assisted FJP were performed on BK7 glass. Other parameters were: nozzle diameter 1 mm, stand-off distance 2 mm, 0.6 μm grit Al_2O_3 abrasives, feed rate 100 mm/min. The Peak-to-Valley (P-V) and Ra values, shown in Fig. 2, were found to



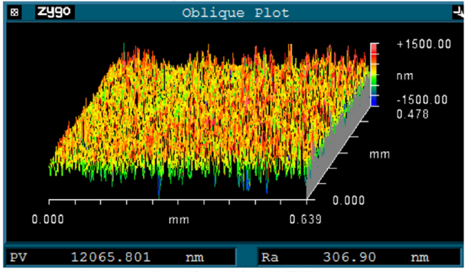
(a) Normal FJP (b) Air-assisted FJP

Fig. 1. Jet plume comparison between normal and air-assisted FJP.



PV 18.047 nm Ra 1.48 nm

(a) Normal FJP



PV 12065.801 nm Ra 306.90 nm

(b) Air-assisted FJP

Fig. 2. Surface roughness comparison in normal and air-assisted FJP.

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worsen by more than 10,000%, leading to the conclusion that air-assisted FJP qualifies more as a blasting than polishing process.

The main issue in these previous attempts at air-assisted FJP lies with the inability to control the size and number of bubbles injected. To solve this shortcoming, a new process is proposed: “ultrasonic cavitation assisted FJP”. In this novel system, an ultrasonic transducer is attached to a specially designed nozzle cavity, and generates gas micro-bubbles within the slurry stream at a location directly upstream of the nozzle outlet. In this process, the size and number of micro-bubbles are controlled through the frequency and intensity of the ultrasonic generator.

In this paper, we report the overall design, numerical modelling, and experimental verification of a prototype system. While this new process presently shows removal rates increase of only up-to 380%, our results also show that it can maintain or even improve surface roughness when compared to normal FJP.

2. Ultrasonic cavitation assisted FJP

2.1. Principle of process

The principle of ultrasonic cavitation assisted FJP is shown in Fig. 3. Slurry is injected on the side of the nozzle cavity, and ejected from a laser-drilled sapphire outlet at the bottom, thereafter it impinges the workpiece surface. At the top, an ultrasonic transducer is affixed to a diaphragm plate, underneath which an acoustic lens is mounted. Guided by the conical shape of the cavity, acoustic waves focus upstream of the nozzle outlet.

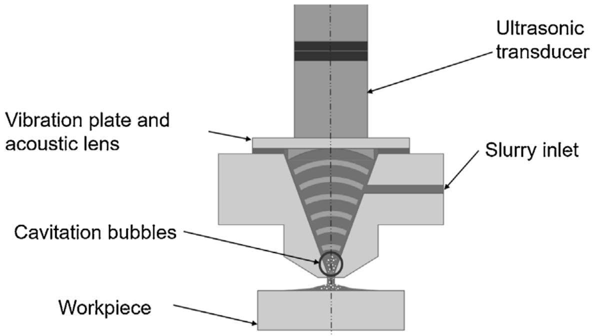


Fig. 3. Principle of ultrasonic cavitation assisted FJP.

For the process to be functional, the ultrasonic equipment and nozzle cavity need to fit several criteria, as follows:

- The dimensions of the cavity should permit the generation of “standing” acoustic waves at the various operating frequencies of the transducer.
- The intensity of pressure waves at the focus point should exceed the operating FJP pressure.
- The travel time from cavitation area to workpiece should be lower than the average lifetime of micro-bubbles.

Numerical simulations were performed to assess the feasibility of this process, and derive the dimensions and specification of the cavity and ultrasonic equipment.

2.2. Numerical modelling

Numerical simulations of the ultrasonic cavitation assisted FJP process were performed with the commercially available “COMSOL” Finite Element Modelling (FEM) software. The modelling consisted of two parts: computational fluid dynamics (CFD) to derive the slurry pressure and velocity in normal FJP conditions, and acoustic vibration analysis (AVA) to predict the propagation of pressure waves generated by the transducer. Rotational symmetry of the system allowed simplification of the model geometry down to a 2D axi-symmetric case, as shown in Fig. 4. FEM simulation parameters are summarized in Table 1.

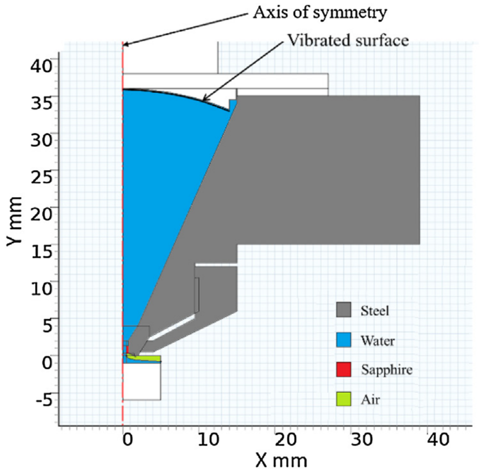


Fig. 4. Geometry of the nozzle cavity in FEM software.

Table 1
Parameters of FEM simulation.

Nozzle geometry			
● Lens diameter	25 mm		
● Lens radius	35 mm		
● Outlet diameter	1 mm		
● Stand-off distance	2 mm		
Ultrasonic parameters			
● Frequency	26 kHz	78 kHz	130 kHz
● Output power	100 W	50 W	25 W

2.2.1. Acoustic vibration analysis

Based on commercial availability of adequate transducers, the simulated AVA frequencies were set to 26, 78 and 130 kHz. Vibrations were applied to the axial direction of the acoustic lens surface, with the displacement acceleration a (mm s^{-2}) relating to the frequency f (Hz) and intensity I (W m^{-2}) of oscillations through the relationship:

$$\alpha = 2\pi f \cdot \sqrt{\frac{2I}{Z_0}} \tag{1}$$

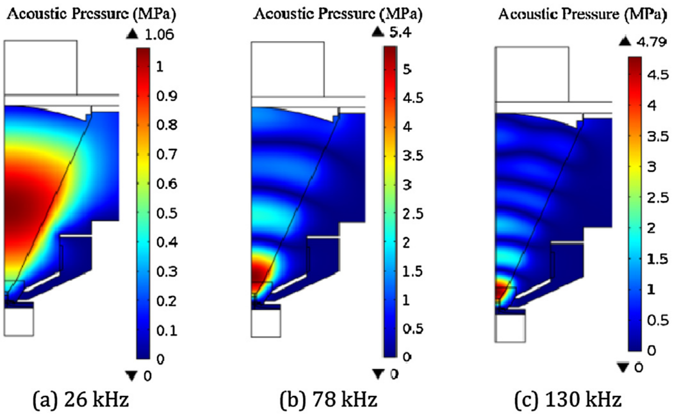
Z_0 (Pa s m^{-3}) is the acoustic impedance, which is determined from the density ρ (kg m^{-3}) and acoustic propagation speed c (m s^{-1}) of the fluid:

$$Z0 = \rho\psi \tag{2}$$

The intensity of oscillations I is determined from the transducer output Q (W) and surface area S (mm^2) of the acoustic lens:

$$I = \frac{Q}{S} \tag{3}$$

In order to obtain standing waves at all frequencies, the nozzle cavity depth was numerically optimized to a value of around 35 mm. AVA simulations, shown in Fig. 5, confirm the sustainability of standing waves by reflection inside the nozzle cavity. For all



(a) 26 kHz (b) 78 kHz (c) 130 kHz

Fig. 5. Simulated distribution of acoustic pressure.

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