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Process mechanism in ultrasonic cavitation assisted fluid jet polishing

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ABSTRACT

Material removal rate in fluid jet polishing is significantly enhanced when ultrasonic cavitation bubbles are introduced at the nozzle outlet. In this paper, two theories are put forward to explain the process mechanism: a micro-scale hypothesis in which the surface is micro-jetted by collapsing bubbles, and a macro-scale hypothesis in which vibration of the fluid in the impingement region increases abrasive particle erosive action. Experimental investigation suggests the higher likelihood of the macro-scale phenomenon, and a material removal model is proposed accordingly. Process footprints simulated by this model were found to agree well with experimental measurements.

1. Introduction

Fluid jet polishing (FJP) is a flexible process for super-fine finishing of small and complex workpiece geometries. A slurry of loose abrasives and carrier fluid is pressurized and pushed out through a nozzle orifice 0.1–1.0 mm in diameter, generating a narrow fluid beam. Impingement of the beam onto a workpiece surface results in a sub-millimeter footprint of time dependent material removal. The principal advantages of FJP include lack of tool wear, ease of access to deeply recessed areas, and the ability to reach nanometer-level surface finish on various materials [1].

However, as compared to micro-waterjet machining, relatively benign processing pressure and abrasive grain size are necessary to achieve smooth polishing in FJP. This results in generally low material removal rate, and long processing time for larger surfaces. To address this issue, an enhancement was proposed in the form of ultrasonic cavitation assisted FJP (UFJP). The principle is shown in Fig. 1: an ultrasonic transducer is fitted with an acoustic lens and mounted at the top of a conical cavity. The focal point of acoustic pressure waves coincides with the outlet of the nozzle, where micro-bubbles are generated by cavitation [2].

When compared to standard FJP, the novel process was found to significantly increase material removal rate by a factor of up-to 380%, as shown in Fig. 2. Furthermore, the final surface roughness was maintained or even slightly improved, a result in sharp contrast with other FJP enhancement systems such as air-bubble injection [3,4].

In this paper, the process mechanism in UFJP is investigated in order to establish the fundamental phenomenon driving the material removal rate boost observed in experimental trials, and understand the influence of the various process parameters. Two possible hypotheses are proposed for the nature of the process mechanism: (1) the mechanism occurs at the micro-scale due to micro-bubble collapse near the workpiece surface, (2) the mechanism occurs at the macro-scale due to vibration of the polishing fluid in the impingement zone. Each hypothesis is investigated through experimental trials, in order to qualify the more likely explanation. Thereafter, a theoretical model of the removal mechanism is proposed that builds upon the generally accepted material removal model for standard FJP, but introduces new parameters accounting for the influence of ultrasonic acoustic waves. Finally, prediction from the model is verified against experimental material removal footprint data.

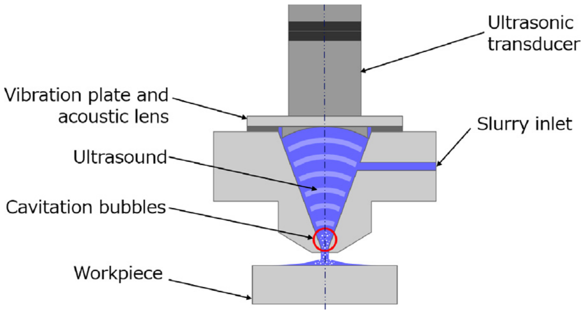
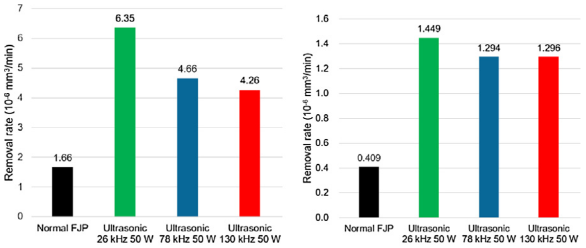


Fig. 1. Principle of ultrasonic cavitation assisted FJP [2].



(a) Electroless nickel (b) BK7 glass

Fig. 2. Material removal rate for 0.6 μm grit and 0.8 MPa [2].

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2. Micro-scale investigation

2.1. Principle of micro-jet formation

Ultrasonic cavitation promotes the formation and growth of micro-bubbles within water, especially in cases where air or other gases are dissolved in the fluid. In cases where such micro-bubbles come near a surface wall (at a distance approximately equal to their diameter), the likelihood of collapse increases due to asymmetric redistribution of surface tension. Fig. 3 shows the principle of micro-bubble collapse near a surface wall: the top side caves-in and a micro-jet punches through the bubble and lurches toward the wall.

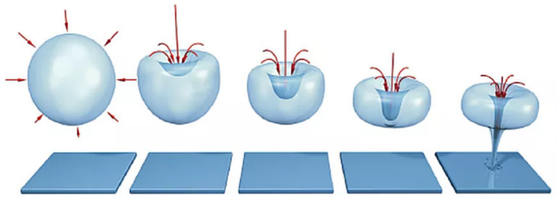


Fig. 3. Principle of micro-bubble collapse near a surface wall, and the resulting micro-jet due to asymmetric redistribution of surface tension [5].

Micro-jet velocities typically in the range 100–500 m/s have been recorded experimentally [6]. Such high fluid displacement velocities result in the so-called water-hammer effect, which causes micro-pit damage to the wall. In cavitation experiments on aluminum sheets, Ye and Zhu [7] measured micro-pit diameters in the range 4–14 μm and depths in the range 0.06–0.88 μm.

In the micro-scale hypothesis for the UFJP mechanism, it is theorized that micro-jetting of the surface by collapsing bubbles results in a combination of strain hardening of the workpiece material and sudden energizing of abrasive particles entrained in the water-hammer zone. Both of these effects would promote a higher removal rate in the regions influenced by micro-jetting.

2.2. Experimental verification

To verify the micro-scale hypothesis, experiments were carried out in which pure water only was injected into the cavitating nozzle (e.g: no abrasives). Optical glass mirrors coated with a layer of aluminum several hundred microns thick were measured by a whitelight interferometer with 50× magnification objective, at the same location before and after processing by the ultrasonic water jet. Experimental conditions are summarized in Table 1.

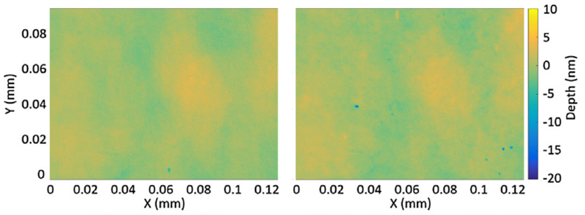
A control experiment was carried out by placing some of the aluminum coated mirrors into an ultrasonic bath cleaning unit, of similar operating frequency to the UFJP system. The system consists of a tank below which 2 transducers of 50 W each are mounted. The samples were suspended in water 67 mm above the bottom of the tank, along the axis of one of the transducers. This control experiment was conducted in order to ensure that micro-pits are indeed generated on the aluminum through the dielectric overcoat, for a power (50 W) and distance (50–60 mm) between transducer and workpiece equivalent to the UFJP setup.

2.3. Results and discussion

The workpieces processed in the control experiment featured numerous micro-pits across the entire surface, and hotspots of higher micro-pit density. Fig. 4(a) and (b) show the same area of a workpiece before and after processing, with the appearance of a dozen larger, and another dozen smaller micro-pits. At hotspots of activity on the surface, over 50 micro-pits in the range 1–4 μm in diameter, and 0.04–0.09 μm in depth, could be observed.

Table 1
Parameters of micro-jet experiment.

Workpiece	
• Dimensions	25 × 25 × 3 mm
• Substrate material	Float glass
• Coating material	Aluminum with dielectric overcoat
• Surface roughness	Ra <2 nm
• Exposure time	60 min
Ultrasonic FJP	
• Operating frequency	22 kHz
• Input power	50 W (focused on impingement zone)
• Nozzle diameter	1 mm
• Pump pressure	0.4 MPa
• Workpiece distance	3 mm (outlet)/53 mm (transducer)
• Working fluid	Pure water
Control experiment	
• Device	Ultrasonic bath cleaner
• Bath dimensions	150 × 75 × 50 mm
• Operating frequency	28 kHz
• Input power	2 × 50 W
• Workpiece distance	67 mm (transducer)
• Working fluid	Pure water



(a) Initial condition
(b) 60 min in ultrasonic bath

Fig. 4. Observations of workpiece processed in control experiment.

By comparison, there was a thorough lack of micro-pit on the surface of all samples processed by water only UFJP. For instance, Fig. 5 shows a series of measurements taken at 1 mm intervals from the center to the edge of the jet impingement zone. The height range for this measurement, between −2 and 12 nm, confirms that no micro-pits are present on the surface.

From the absence of micro-pits on the UFJP processed samples, it is assumed that micro-jetting of the surface by micro-bubbles either did not occur in the impingement region, or that the water-hammer pressure was so negligible that plastic deformation of the aluminum coating did not occur. In the first case, the most plausible explanation is that micro-bubbles cannot penetrate the near-wall fluid shear layer, and simply follow fluid streams in the layer above. In either case, it may be safely assumed that micro-jetting is not a major factor influencing the material removal mechanism in UFJP. Consequently, the micro-scale hypothesis may be considered as the least likely explanation for the increased removal rate in UFJP.

3. Macro-scale investigation

3.1. Sources of fluid vibration

In the macro-scale hypothesis, the increase in material removal rate is theorized to issue from additional erosive action of the

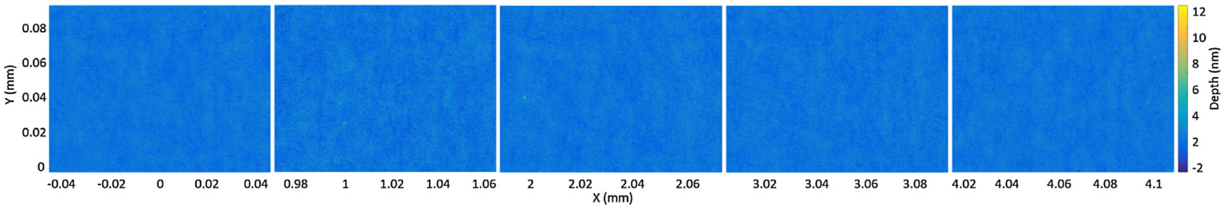


Fig. 5. Observation at regular intervals from centre-to-edge of the jet impingement zone on workpiece processed 60 min by 22 kHz UFJP.

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