DEVELOPMENT OF CAVITATION AIDED MACHINING
FOR FINISHING FINE SURFACE

Kazuhiro Ohashi*, Shinya Tsukamoto*, Toshikatsu Nakajima**
* Okayama University, 3-1-1 Tsushima-naka, Okayama, 700-8530, JAPAN
** Professor Emeritus of Okayama University, 2317-4 Sayama, Okayama, 701-1205, JAPAN

1. Introduction
Cavitation was discovered at the end of the 19th century. For more than one century since the discovery, mechanical engineers have been troubled with a cavitation which causes a generation of the erosion, vibration and noise of a fluid machinery.

In this paper, the cavitation aided machining as a precision manufacturing method is proposed, based on the new concept using positively the cavitation in a suction flow for machining phenomenon. That is to say, this manufacturing method makes loose abrasive grains, which are mixed with water as a carrier, to interfere in the workpiece surface with impact of the cavitation and flow of the machining fluid restricted partially by the restrictor above a machining point on workpiece surface. A fundamental machining phenomenon in cavitation aided machining of glass surface is made clear and its machining performance is experimentally investigated by analyzing surface finish, stock removal and cavitation impact. Then an efficiency of applying the cavitation aided machining as a precision surface finishing is proved by carrying out surface finishing on glass surface in the order of nanometers based on the machining phenomenon.

2. Principle of Cavitation Aided Machining and Experimental Procedure

Fig. 1 shows a schematic view of the fundamental apparatus of the cavitation aided machining. This apparatus mainly consists of a chamber of machining fluid, a restrictor and a suction pump. When machining fluid filled in the camber is sucked with a pump, cavitation occurs partially in a suction flow under a restrictor setting in the passageway as shown in this figure. This machining method makes loose abrasive grains, which are mixed with machining fluid, to interfere the workpiece surface with impact of the cavitation and flow of the machining fluid by the restrictor just above workpiece surface. Main machining conditions are shown in table 1. The shape of restrictor is a semicircular disc of 20mm in radius. The suction pump used in test has an ability of 0.075m³/min in rated discharge and 7.5m in head-capacity. Workpiece surface is polished down to about 9.3nmRy in surface finish before tests. Surface finish is measured with Rank Taylor Hobson Nanostep. In this machining, the interference intensity of loose abrasives is influenced by the cavitation impact generated by collapsing bubbles. However, it is too difficult to measure the intensity of cavitation impact because it increases up to several giga-pascals during several micro-seconds in very small area [1]. The cavitation intensity is measured by a miniature quartz force transducer (Kistler Type 9211) fixed under a hole of 1.3mm in bore drilled through from workpiece surface. Measured data is stored in a digital storage oscilloscope (200MHz in sampling rate).

3. Machining Phenomenon and Performance in Cavitation Aided Machining

Fig. 2 shows the variation of stock removal $S$ under a restrictor in cavitation aided machining. The stock removal is extremely small just under the restrictor tip ($y=0$) and it increases with increasing the distance from restrictor tip $y$ within 12.5mm in $y$ in which stock
removal is maximum. In order to make clear such peculiar variation of stock removal, the distribution of cavitation impact $P_c$ on the workpiece surface in a machining process is shown in this figure. The cavitation impact is slightly generated under a restrictor tip ($y=0$). It increases with increasing the distance from restrictor tip and has the maximum at about 12.5 mm in $y$. Furthermore it decreases with increasing $y$ in downstream form its maximum point. Such variation of cavitation impact is similar to that of stock removal and the point of maximum cavitation impact closely agree with that of maximum stock removal. This suggests as follows. Bubbles with cavitation are mainly generated and grow up near the restrictor tip, and then bubbles collapse after flowing away from the restrictor tip because of increasing pressure of machining fluid by increasing the cross-sectional area of passageway. At the moment of collapsing bubbles, the impact for interfering acts loose abrasive grains flowing in machining fluid.

Fig. 3 shows the effect of loose abrasive grain size on stock removal $S$ at the workpiece surface downstream of the restrictor tip. Stock removal increases with larger gain size, and workpiece material just under the restrictor tip ($y=0$), on which cavitation impact weakly generates, is remarkably removed because of the flow of machining fluid mixed with abrasive grains in the cases of grain size larger than #2500. In any cases of grain size, the stock removal increases with increasing the distance from restrictor tip $y$ and it has the maximum at about 12.5 mm in $y$. Such variations of stock removal depend on the distribution of cavitation impact on machining area of workpiece surface as shown in fig. 2.

Fig. 4 shows the effect of loose abrasive grain size on surface finish $R_y$ at the surface downstream of the restrictor tip. The initial surface roughness of 9.3 nm in maximum height is shown with a straight dotted line. The surface finish decreases with finer grain size and its variation is not similar to the stock removal. Improving surface finish down to about 5 nm in maximum height partially, cavitation aided machining with WA4000 has a most suitable effect for finishing glass surface. Surface finish with #8000, almost as large as the initial surface roughness, is larger than that with #4000. Such results suggest that the kinetic energy of each acting loose abrasive grain supplied by sucked cavitation flow decreases with decreasing the grain size. However, the finishing ability of cavitation aided machining with WA8000, which is about 1.2 µm in average diameter, is lower than that with another grain size because of too small kinetic energy of abrasive grain for enough machining effect in 30 minutes.

Fig. 5 shows a DFM observation of finished glass surface with WA4000. A fine surface, with a lot of very small

![Fig. 3 Effect of loose abrasive grain size on stock removal](image1)

![Fig. 4 Effect of loose abrasive grain size on surface finish](image2)
dimples of several nano-meters in depth, is generated by cavitation aided machining. It is considered that such small dimples are generated by mild interference of loose abrasive grains applied a cavitation impact on workpiece surface.

**Fig. 6** shows the effects of abrasive grain material on stock removal $S$ and surface finish $R_y$. And **Table 2** shows characteristics of three kinds of abrasive grain used in test. AZ grain is produced by mixing alumina abrasive with zirconia abrasive of 30%wt. which is about 1300 in knoop hardness.

The stock removal becomes the maximum at 12.5mm in $y$ with any kinds of abrasive grains because of the maximum cavitation impact at the point. And the stock removal with AZ grain is larger than that with WA grain which is similar to that with GC grain. Such results indicate that the kinetic energy of AZ grain applied with cavitation and flowing of machining fluid is larger than those of another grains because of its larger specific gravity. While the surface finish becomes smaller in the order, GC, AZ, WA grain, and surface finish with GC grain is especially larger than the initial surface roughness. It is considered that taking part each other, the effect of characteristics of abrasive grains appeared on such result of surface finish. That is, the interference intensity of GC grain is larger than that of WA grain because of higher hardness of GC grain. AZ grain acts on the workpiece surface stronger than WA grain, as the result that AZ grain including zirconia abrasive is softer than WA grain but its specific gravity is larger than that of WA grain. Therefore cavitation aided machining leads the mechanical material removal in very small scale by interference of loose abrasive grains.

### 4. Finishing Fine Surface

The above mentioned investigation makes clear the fundamental machining phenomenon in cavitation aided machining of glass and its effective conditions for finishing fine surface. So fine glass surface should be finished by applying such machining phenomenon.

**Fig. 7** shows a schematic view of the surface finishing apparatus by the cavitation aided machining. Main constructions of the apparatus are almost as same as shown in Fig. 1 except for a restrictor slid parallel to the workpiece surface along the flowing direction in the extended intake by a ball screw and a synchronous motor. Main finishing conditions are shown in **Table 3**.

**Fig. 8** shows variations of stock removal $S$ in surface finishing process by cavitation aided machining. The restrictor slides once back and forth between 70mm and 0mm in $y$ with a setting rate $v_r$. The stock removal is approximately

<table>
<thead>
<tr>
<th>Grain</th>
<th>WA</th>
<th>GC</th>
<th>AZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific gravity</td>
<td>3.98</td>
<td>3.98</td>
<td>4.22</td>
</tr>
<tr>
<td>Knoop hardness</td>
<td>2050</td>
<td>2550</td>
<td>—</td>
</tr>
</tbody>
</table>

**Table 2** Characteristics of loose abrasive grain used in test

![DFM observation of machined glass surface with WA4000](image_url)

**Fig. 5** DFM observation of machined glass surface with WA4000

![Effects of loose abrasive grain on stock removal and surface finish](image_url)

**Fig. 6** Effects of loose abrasive grain on stock removal and surface finish
constant except near both sliding ends of restrictor at any sliding rates. In the case of 0.8mm/min in sliding rate, fine surface less than 20nm in flatness is generated through about 60mm in length.

Fig. 9 shows the effect of surface finish $R_y$ on sliding rate of restrictor $v_r$ in surface finish process by cavitation aided machining. Surface finish decreases with decreasing sliding rate of restrictor and is smaller than that of initial surface. In the case of 0.8mm/min in $v_r$, in which stock removal is largest in the setting region of sliding rate in the test, surface finish is improved down to 7.6nm in maximum height but is larger than that in the fundamental test shown in fig. 4. Therefore such results will indicate the possibility of ultraprecision finishing of glass surface by cavitation aided machining.

5. Conclusions
Main conclusions obtained in this paper are as follows.
(1) Cavitation aided machining, as improved the surface finish of glass down to about 5.0nm in maximum height by using abrasives of WA 4000, has a possibility for applying to an ultraprecision finishing.
(2) WA grains generate finer machined surface than GC abrasives that is harder or AZ abrasives that have higher specific gravity.
(3) Fine finished glass surface with 60mm in length is generated by applying a fundamental machining phenomenon of cavitation aided machining along flowing direction of machining fluid continuously.

References