



ELSEVIER

Contents lists available at ScienceDirect

## International Journal of Machine Tools &amp; Manufacture

journal homepage: [www.elsevier.com/locate/ijmactool](http://www.elsevier.com/locate/ijmactool)

# Fabrication of deep micro-holes in reaction-bonded SiC by ultrasonic cavitation assisted micro-EDM

Pay Jun Liew<sup>a,c</sup>, Jiwang Yan<sup>b,\*</sup>, Tsunemoto Kuriyagawa<sup>a</sup><sup>a</sup> Department of Mechanical Systems and Design, Tohoku University, Aramaki Aoba 6-6-01, Aoba-ku, Sendai 980-8579, Japan<sup>b</sup> Department of Mechanical Engineering, Faculty of Science and Technology, Keio University, Hiyoshi 3-14-1, Kohoku-ku, Yokohama 223-8522, Japan<sup>c</sup> Manufacturing Process Department, Faculty of Manufacturing Engineering, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia

## ARTICLE INFO

## Article history:

Received 21 April 2013

Received in revised form

8 September 2013

Accepted 22 September 2013

Available online 30 September 2013

## Keywords:

Ultrasonic vibration

Cavitation

Micro-electro discharge machining

Carbon nanofiber

Reaction-bonded silicon carbide

Ceramic material

## ABSTRACT

Ultrasonic vibration was applied to dielectric fluid by a probe-type vibrator to assist micro electrical discharge machining of deep micro-holes in ceramic materials. Changes of machined hole depth, hole geometry, surface topography, machining stability and tool material deposition under various machining conditions were investigated. Results show that ultrasonic vibration not only induces stirring effect, but also causes cloud cavitation effect which is helpful for removing debris and preventing tool material deposition on machined surface. The machining characteristics are strongly affected by the vibration amplitude, and the best machining performance is obtained when carbon nanofibers are added into the vibrated dielectric fluid. As test pieces, micro-holes having 10  $\mu\text{m}$  level diameters and high aspect ratios ( $> 20$ ) were successfully fabricated on reaction-bonded silicon carbide in a few minutes. The hybrid EDM process combining ultrasonic cavitation and carbon nanofiber addition is demonstrated to be useful for fabricating microstructures on hard brittle ceramic materials.

© 2013 Elsevier Ltd. All rights reserved.

## 1. Introduction

Electrical discharge machining (EDM) is one of the most popular unconventional machining processes used for producing complex shapes that are difficult to machine using other conventional processes. In EDM, a tool and a workpiece are submerged in a dielectric fluid, and the workpiece material is removed by means of repetitive spark discharges from electric pulse generators [1–2]. EDM has many advantages, such as low installation cost and capability to machine complex three-dimensional shapes easily in spite of material hardness [3]. In recent years, micro-EDM is strongly expected to be used for generating three-dimensional microstructures, such as micro-holes, micro-grooves and micro-dimples, on reaction-bonded silicon carbide (RB-SiC).

However, due to the narrow sparking gap in micro-EDM, the removal of debris is remaining a challenging issue, especially in deep hole machining and fine finishing with lower discharge energy. When the debris concentration at the bottom of the gap between the electrode and workpiece reaches a certain critical value, it will not only deform the machined geometry [4], but also lower the surface integrity of the workpiece by forming micro-cracks and thickened heat affected zones [5].

To overcome these problems, several approaches have been attempted by previous researchers, such as orbital electrode actuation [6], flushing [7,8], planetary movement of electrode [9], ultrasonic vibration of workpiece [10], dielectric fluid tank [11] and tool [12]. Ultrasonic vibration has also been carried out in combination with other process improvements, such as EDM using non-circular electrode [13,14], planetary movement of tool [15], helical micro-tool [16], and micro-powders [17]. The use of ultrasonic cavitation in macro-EDM of carbon fiber reinforced plastic (CFRP) to remove debris also has been attempted [18]. However, whether ultrasonic cavitation is effective or not in micro-EDM has not been clarified yet, especially in micro-EDM of deep micro-holes of ceramic materials.

In this paper, ultrasonic vibration was directly applied to the dielectric fluid in the machining region by using a probe-type vibrator (instead of vibrating the dielectric tank) to generate cavitation to assist micro-EDM of deep micro-holes in RB-SiC. The effect of ultrasonic vibration was investigated in combination with the addition of carbon nanofibers into dielectric fluid. As shown in the previous paper of the present authors [19], by adding carbon nanofibers in the dielectric fluid, the electrical discharge machinability of RB-SiC can be significantly improved. However, there are still problems such as tool material deposition on workpiece surface [20], and the machining efficiency is distinctly lower compared with the EDM of metal materials. In the present study, a hybrid EDM process by combining ultrasonic

\* Corresponding author. Tel.: +81 455661445; fax: +81 455661495.

E-mail address: [yan@mech.keio.ac.jp](mailto:yan@mech.keio.ac.jp) (J. Yan).

cavitation and carbon nanofiber addition is proposed to improve machining efficiency, surface quality and form accuracy of deep micro-holes in RB-SiC ceramic material.

## 2. Experimental

### 2.1. Method

The proposed hybrid micro-EDM method by combining ultrasonic cavitation and carbon nanofibers addition is schematically shown in Fig. 1(a). A suitable amount of carbon nanofibers are added and mixed in the dielectric fluid and then a probe-type oscillator horn is placed into the dielectric fluid over the workpiece. When ultrasonic vibration is applied to the dielectric fluid, intense ultrasonic waves travel through the liquid, generating small cavities that enlarge and collapse. This phenomenon is called as cavitation [21]. In conventional EDM, the debris is removed by gaseous bubbles escaping from the working area through the discharge gap [15,22]. In this study, instead of gaseous bubbles, the ultrasonic cavitation will dominate the removal of discharge-induced debris. Thus, stable machining performance might be obtained.

The probe-type vibrator (oscillator horn) used in this study enables concentrative vibration of the dielectric fluid in the machining region, whereas the unmachined regions are less affected. Therefore, very strong ultrasonic cavitation may be generated at very low energy consumption. From this meaning, the vibration mechanism in this study is distinctly different from those in traditional ultrasonic vibration which is applied to the dielectric tank.

On the other hand, carbon nanofibers play an important role in the EDM process of low-conductivity RB-SiC material, as shown previously [19,20]. The excellent electrical conductivity of carbon nanofiber can reduce the insulating strength of the dielectric fluid and increase the spark gap distance, leading to a high material removal rate and better surface finish. In the hybrid EDM method, the ultrasonic vibration of dielectric fluid causes strong stirring effect which prevents the carbon nanofibers from aggregation, so that the nanofibers disperse uniformly in the dielectric fluid. As a result, frequency of electro discharge in the EDM of RB-SiC might be improved.

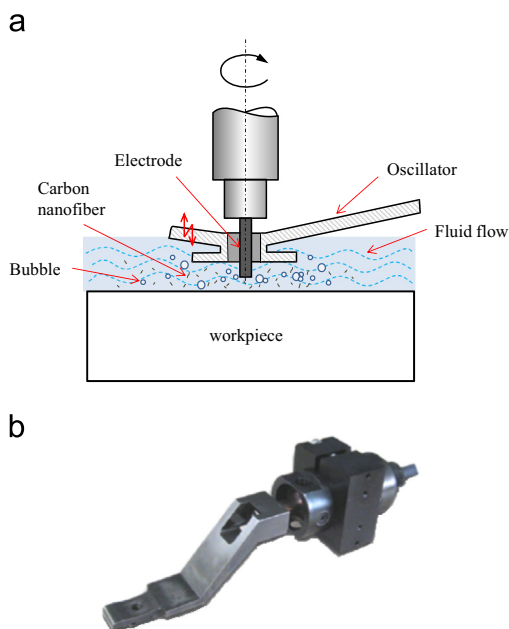


Fig. 1. (a) Schematic diagram of the proposed hybrid micro-EDM process and (b) photograph of the probe-type oscillator horn used in the experiment.

### 2.2. Experimental setup

A micro-EDM machine, Panasonic MG-ED82W, produced by Matsushita Electric Industrial Co., Ltd., was used in this experiment. This machine is energized by a resistor-capacitor (RC) type pulse generator. The electrical capacitance is determined by condensers C1–C4, where the capacities are 3300 pF, 220 pF, 100 pF and 10 pF, respectively. This machine is capable of doing micro-wire EDM and micro-die sinking machining, with a stepping resolution of 0.1  $\mu\text{m}$ . To excite vibration of dielectric fluid, a probe-type ultrasonic cavitation generator (Fig. 1b) SC-450 (Taga Electric Co., Ltd., Japan) [23] with a power output of 50 W was used in this experiment. It has vibration frequency of 20 kHz and maximum amplitude of 14  $\mu\text{m}$ . During the EDM process, the tool electrode was inserted through the hole at the end of the oscillator horn of the cavitation generator. The oscillator horn was placed 2–3 mm from the workpiece. Ultrasonic vibration was applied to the dielectric fluid directly by the oscillator horn, which causes the cavitation effect.

### 2.3. Materials

An important ceramic mold material, RB-SiC, was used as workpiece in this study. The RB-SiC material composed of 6H-SiC grains (grain size  $\sim 1 \mu\text{m}$ , 88% in volume) and a Si matrix (12% in volume). The as-received samples were cylinders with a diameter of 30 mm and a thickness of 10 mm. The electrical resistivity of the sample is 1453  $\Omega \text{ cm}$ . The tool electrode used in this experiment was tungsten. Commercially available EDM oil, Casty Lube EDS (Nikko Casty Co., Ltd.) was used as dielectric fluid. High conductivity carbon nanofibers, 150 nm in diameter and 6–8  $\mu\text{m}$  in length, were used as an additive in dielectric.

### 2.4. Machining conditions

First, effect of vibration amplitude on machining efficiency was investigated. For comparison, two types of micro-EDM tests were carried out, namely, (1) ultrasonic cavitation in pure EDM oil, and (2) ultrasonic cavitation in EDM oil mixed with carbon nanofibers. Micro-hole machining was performed on the sample for duration of specified time, and average of three tests for each parameter setting was taken. Electrode dressing was performed after each EDM cycle by using wire electro discharge grinding (WEDG) in order to improve the form accuracy. Table 1 shows the experimental conditions.

Table 1  
Experimental conditions.

Workpiece material	RB-SiC
Electrode material	Tungsten
Polarity	Positive (workpiece) Negative (tool)
Rotational speed (rpm)	3000
Feed rate ( $\mu\text{m/s}$ )	3
Voltage (V)	70, 100
Condenser capacitance (pF)	Stray capacitance, 3300
Vibration frequency (kHz)	20 $\pm$ 1.5
Vibration amplitude ( $\mu\text{m}$ )	0–14
Dielectric fluid	EDM oil (CASTY-LUBE EDS)
Additive	Carbon nanofibers (CNFs)
CNFs size ( $\mu\text{m}$ )	Diameter=0.15, Length=6–8
Concentration (g/L)	0.06
Machining time (s)	30–150

2.5. Measurement and evaluation

In order to examine the microstructure of the samples, surface topography of the machined micro-holes was examined by a scanning electron microscope (SEM), SU1510 (Hitachi, Co., Ltd.). The depth, surface roughness and cross-sectional profile of micro-holes after the EDM tests were measured using a laser probe profilometer NH-3SP (Mitaka Kouki Co. Ltd.). The measurement of surface roughness was performed across the center of the micro cavity along the radial direction, and the evaluation length was 100  $\mu\text{m}$ . Energy dispersive X-ray spectroscopy (EDX) was used to detect material migration and measure the amount of migrated material. In order to clarify the machining stability, tool electrode

movement in the Z-direction during EDM test was captured using a Keyence high speed camera, and then VW9000 Motion Analyzer software was used to track the movement of the electrode.

3. Results and discussion

3.1. Effect of vibration amplitude

Fig. 2 illustrates the effect of vibration amplitude on the depth of machined micro hole, with 0.06 g/L carbon nanofibers concentration in the dielectric fluid. The machining time for each test was 2 min. It is seen that the depth of machined hole increases rapidly

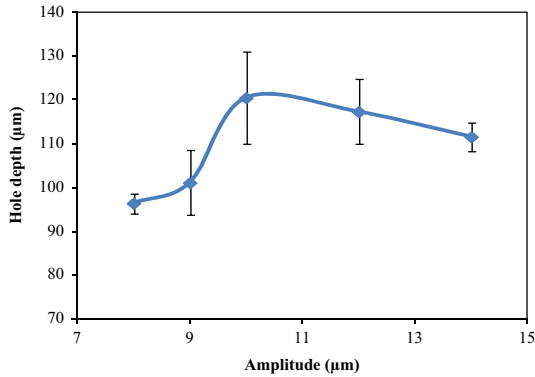


Fig. 2. Effect of vibration amplitude on depth of machined micro-hole.

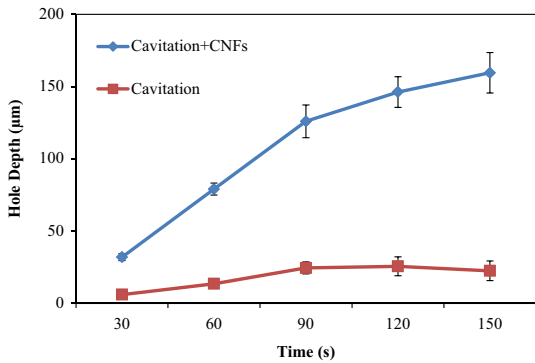


Fig. 3. Change in depth of micro-hole with time when ultrasonic cavitation is used in dielectric oil with/without CNF addition.

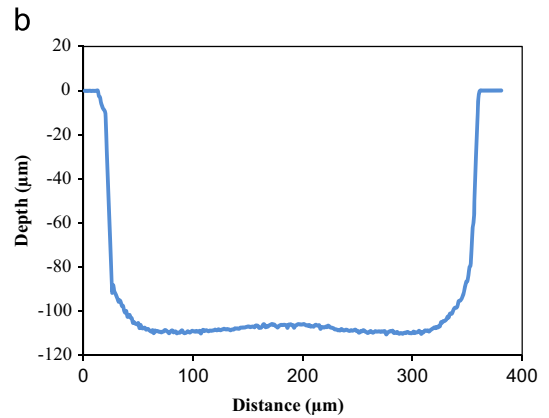
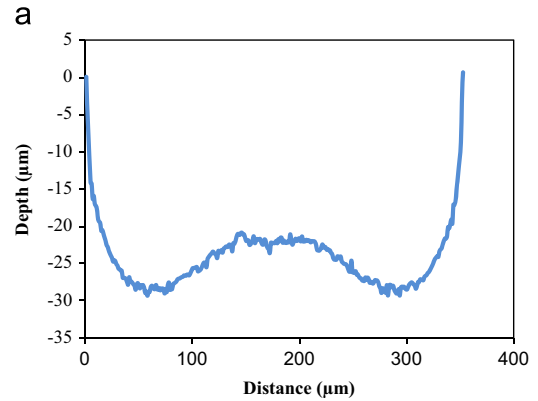


Fig. 5. Comparison of cross-sectional profiles of micro-holes machined with ultrasonic cavitation in (a) pure EDM oil and (b) carbon nanofibers mixed EDM oil.

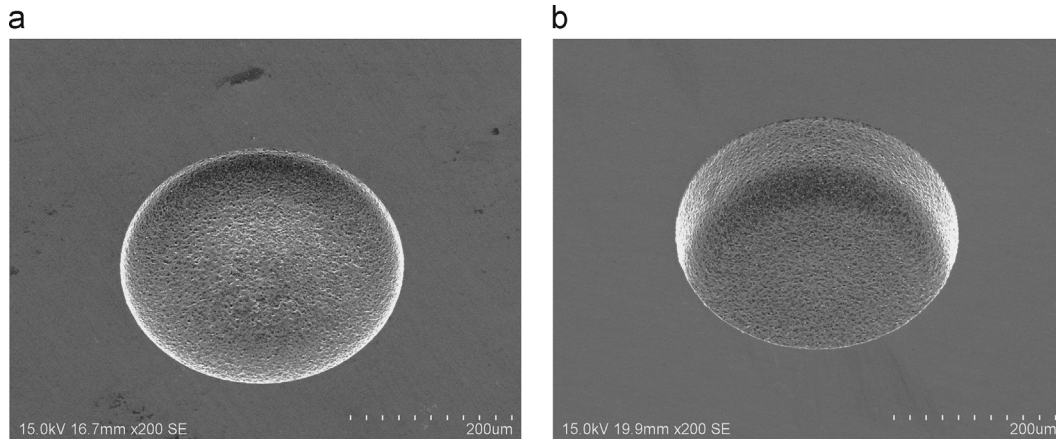


Fig. 4. SEM micrographs of micro-holes after machining time of 2 min with ultrasonic cavitation in (a) pure EDM oil and (b) carbon nanofibers mixed EDM oil.

when the amplitude increased from 8  $\mu\text{m}$  to 10  $\mu\text{m}$ . However, when the amplitude increases further, the depth of machined hole tends to decrease. At excessively high amplitude, the increase in number of cavitation bubbles might block the dielectric fluid from flowing into the sparking gap. This phenomenon makes the machining process unstable, leading to the reduction of material removal rate. The results in Fig. 2 indicate that the optimum vibration amplitude for increasing the material removal rate is 10  $\mu\text{m}$ .

### 3.2. Hybrid effect of ultrasonic cavitation and carbon nanofiber addition

Fig. 3 shows changes in machined hole depth under conditions (1) ultrasonic cavitation in pure EDM oil, and (2) ultrasonic cavitation in carbon nanofibers mixed EDM oil, respectively. The vibration amplitude in this case is 10  $\mu\text{m}$ . Compared to using ultrasonic cavitation in pure EDM oil, when using ultrasonic cavitation in carbon nanofibers mixed EDM oil the material

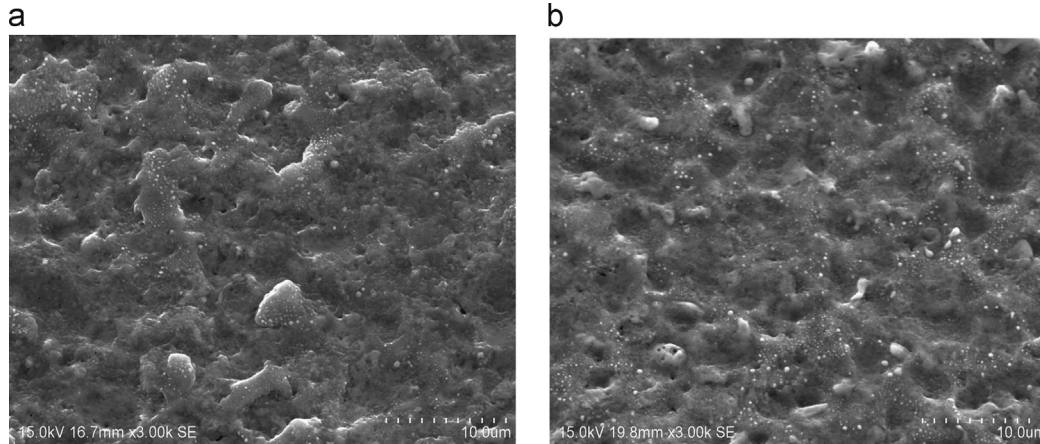


Fig. 6. SEM micrographs of machined surfaces after machining time of 2 min with ultrasonic cavitation in (a) pure EDM oil and (b) carbon nanofibers mixed EDM oil.

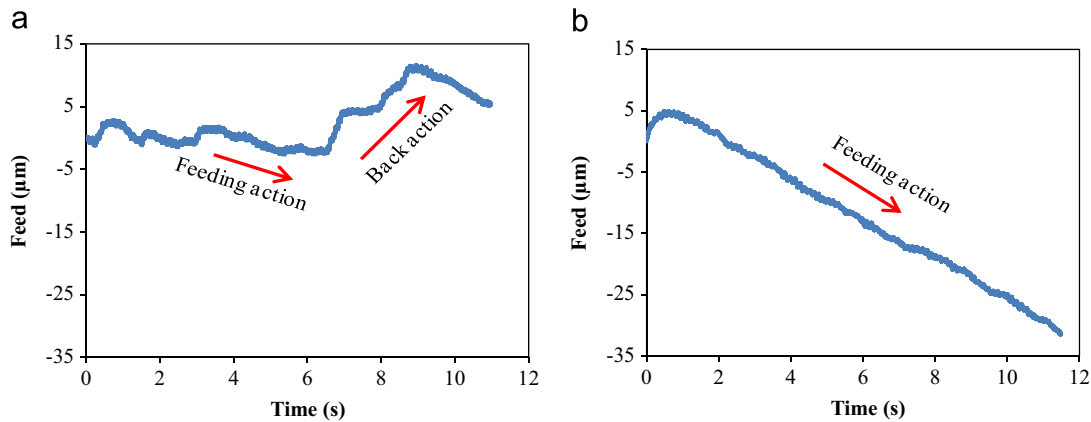


Fig. 7. Measurement results of electrode movement with ultrasonic cavitation in (a) pure EDM oil and (b) carbon nanofibers mixed EDM oil.

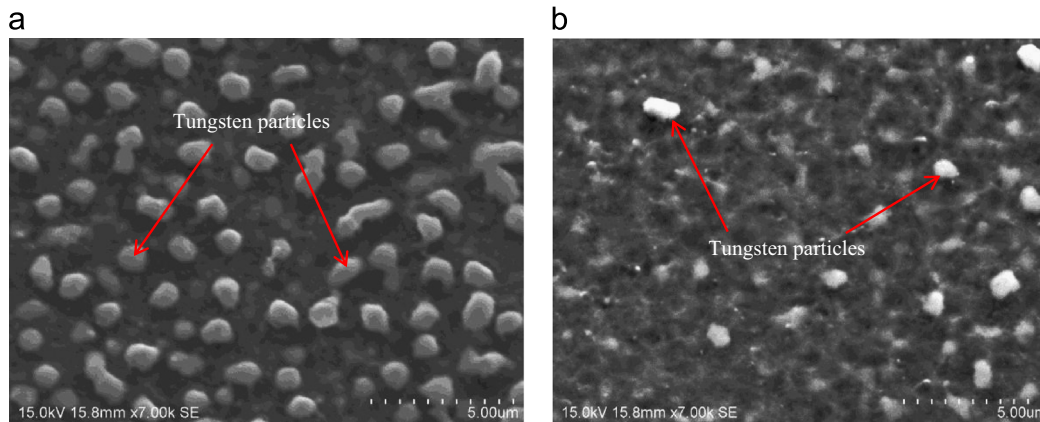


Fig. 8. SEM micrograph of surface machined with carbon nanofibers addition and (a) without ultrasonic cavitation and (b) with ultrasonic cavitation.

removal rate and the depth of micro hole is increased by 5–7 times. Due to the vibration-induced cavitation bubbles and strong stirring effect, the carbon nanofibers are distributed uniformly in the machining region without aggregation. As a result, the carbon nanofibers can fully play their role in EDM, leading to increases in discharge gap, discharge frequency and material removal rate. From this meaning, there is a kind of synergistic effect between ultrasonic cavitation and carbon nanofiber addition for improving machining performance in the micro-EDM of RB-SiC.

### 3.3. Micro hole geometry

Next, hole geometry after EDM was investigated. Fig. 4 presents SEM micrographs of machined micro-holes obtained with ultrasonic cavitation in pure EDM oil and carbon nanofibers mixed EDM oil. Fig. 5a and b shows typical cross-sectional profiles of the micro-holes shown in Fig. 4a and b, respectively. The profiles were measured by laser probe profilometer NH-3SP. It is clear that with ultrasonic cavitation in pure EDM oil (Figs. 4a and 5a), a cone shape protrusion was formed in the center of the micro hole. However, when ultrasonic cavitation is used in carbon nanofibers mixed EDM oil, as shown in Figs. 4(b) and 5(b), the bottom of the micro-hole became flat. At the same time, the depth of micro-hole is remarkably deeper in Fig. 5(b) compared to the one in Fig. 5(a).

In pure EDM oil, stagnation of debris occurs easily at the center of micro-cavities where the debris interacts with the tool electrode [4]. This phenomenon causes concavity at the center of tool tip [4,19]. When carbon nanofibers are added into the dielectric fluid, however,

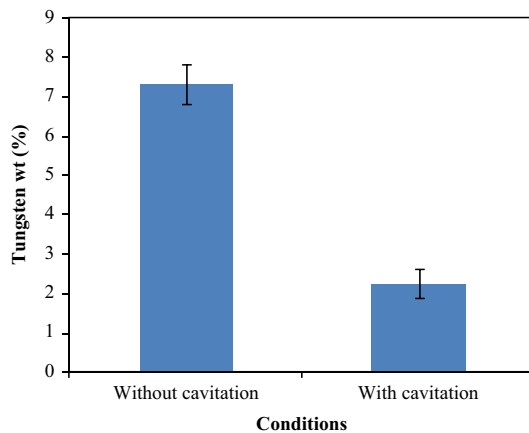


Fig. 9. Weight percentage of deposited electrode material with/without cavitation.

the insulating strength of dielectric fluid will be reduced, and a bigger discharge gap is obtained between the tool electrode and the workpiece [19]. Thus, debris will be flushed out effectively with the help of ultrasonic cavitation bubbles and debris concentration at the center of micro-hole will be prevented. This indicates again that the combination of ultrasonic cavitation and addition of carbon nanofibers in the dielectric fluid, rather than using either of them alone, is essential.

### 3.4. Surface topography

Fig. 6 shows SEM micrographs of the machined surface. With ultrasonic cavitation in pure EDM oil, the surface of the micro-hole is very rough ( $0.28 \mu\text{mRa}$ ) and covered with resolidified material (Fig. 6a). In contrast, in Fig. 6(b), the surface machined with ultrasonic cavitation in carbon nanofiber mixed EDM oil is smoother ( $0.20 \mu\text{mRa}$ ), and surface craters are remarkably smaller. Different from vibration-assisted EDM of metal materials [24], the material removal mechanism in vibration-assisted EDM of RB-SiC involves spalling of large flakes, leading to a rough surface. However, the spalling of large flakes can be prevented by the hybrid EDM process using ultrasonic cavitation and carbon nanofiber addition in the dielectric fluid.

### 3.5. Stability of machining process

As the EDM machine employs an automatic feed control system, if short circuit occurs because of tool-workpiece contact or adhesion of debris, then the tool electrode is moved in the reverse direction of the feed to maintain the tool-workpiece gap.

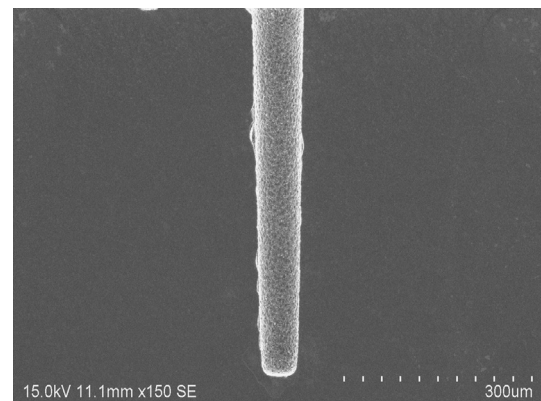


Fig. 11. SEM micrograph of a cross-sectioned high aspect ratio micro hole.

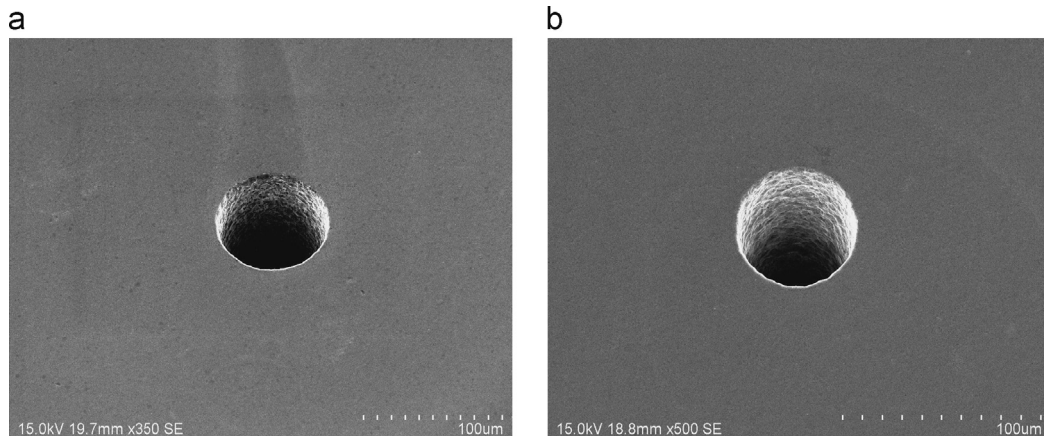


Fig. 10. Micro-holes obtained with (a)  $50 \mu\text{m}$  and (b)  $23 \mu\text{m}$  diameter tool electrodes.

This back-feeding action indicates the EDM process is unstable and results in the increase of machining time [25]. In this study, in order to investigate the machining stability, we captured and tracked the electrode movement.

Fig. 7 shows the measurement results of electrode movement when ultrasonic cavitation was used in pure EDM oil and carbon nanofibers mixed EDM oil. Frequent back-feeding actions occurred in Fig. 7a, indicating the occurrence of abnormal discharge and unstable machining situation. In Fig. 7b, however, continuous feeding action of electrode toward the workpiece is observed without reverse action. This result demonstrates again that the hybrid process of ultrasonic cavitation and addition of carbon

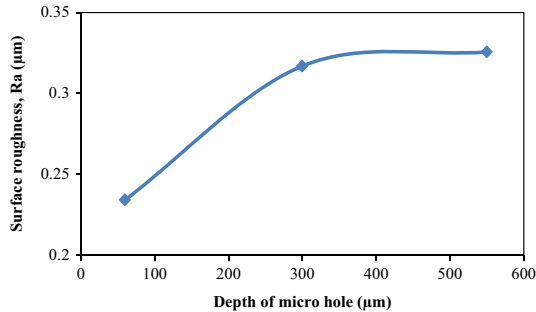


Fig. 12. Surface roughness at different depth of micro hole.

nanofibers in dielectric fluid improves the process stability and material removal rate.

### 3.6. Effect of ultrasonic vibration on tool material deposition

Fig. 8 presents SEM micrographs of surface machined at low energy for fine machining (70 V, stray capacitance,) with carbon nanofibers addition in dielectric fluid (concentration 0.06 g/L) with/without ultrasonic vibration. Without ultrasonic cavitation, many tungsten particles are deposited on the workpiece surface (Fig. 8a). In contrast, with ultrasonic cavitation the tungsten particle deposition is reduced significantly (Fig. 8b).

Fig. 9 shows tungsten weight percentage analyzed by EDX for both conditions. The weight percentage of deposited tungsten decreases by a factor of 3 by using ultrasonic cavitation. With ultrasonic cavitation, the cavitation bubbles oscillate rapidly at the working area, preventing the tungsten debris deposition.

### 3.7. Fabrication of high aspect ratio micro-hole

Next, we attempted to fabricate high aspect ratio micro-holes using the hybrid effects of ultrasonic cavitation and carbon nanofiber addition in dielectric fluid. Tungsten rods with diameters of 50 μm and 23 μm were used as tool electrodes. SEM micrographs of the machined micro-holes are shown in Fig. 10. An aspect ratio of 11.5 was achieved within 10 min by using the

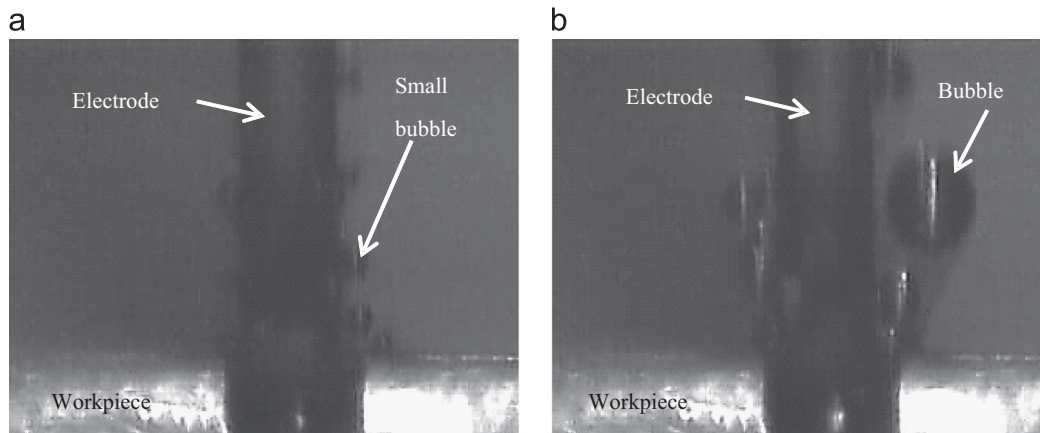


Fig. 13. High speed camera observation of micro-EDM without ultrasonic cavitation: (a) early stage and (b) later stage.

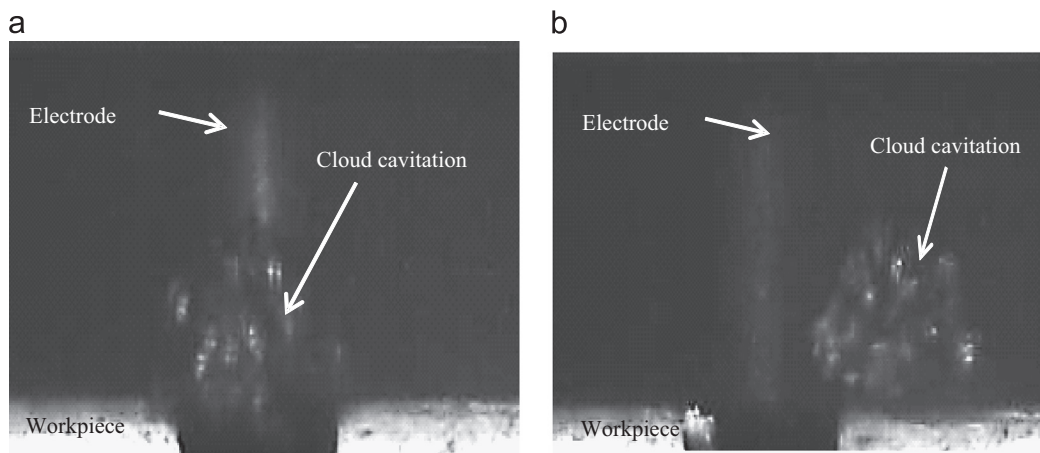


Fig. 14. High speed camera observation of micro-EDM with ultrasonic cavitation, showing (a) cloud cavitation formation and (b) oscillation of cloud cavitation.

50  $\mu\text{m}$  diameter tool, and an aspect ratio of 21.7 was obtained with the 23  $\mu\text{m}$  electrode in 4 min.

In order to examine the inner surface quality of the high aspect ratio micro-hole, the sample in Fig. 10(a) was cross-sectioned by a diamond cutter and polished using diamond slurry and observed by SEM. Fig. 11 shows an SEM micrograph of the hole cross section. The bottom of the micro-hole is flat without cone shape protrusion. The surface roughness of hole side walls were then measured using the laser probe profilometer at three locations of different hole depths. As shown in Fig. 12, the surface roughness ranges from 0.24 to 0.32  $\mu\text{mRa}$  and does not show obvious change with the depth of micro-hole. This result indicates that the ultrasonic cavitation is effective even at the deep region of the micro-hole.

#### 4. Process mechanism

To reveal the hybrid micro-EDM process mechanism, we observed the machining tests with/without ultrasonic cavitation using a high speed camera. To ease observation, the RB-SiC workpiece was attached to a plate of glass, and EDM tests were performed along the interface of RB-SiC and glass. High speed camera observation was done from the glass side perpendicularly to the feed direction of the tool electrode. In this way, cavitation bubbles can be clearly seen through the transparent glass. As shown in Fig. 13, without ultrasonic cavitation, lots of small

bubbles are created first (Fig. 13a), and then these small bubbles continue to grow in size until they finally collapse (Fig. 13b). In contrast, with ultrasonic cavitation, the cavitation bubbles tend to accumulate, forming cloud cavitation (Fig. 14a). These clouds cavitation oscillate around the working area rapidly, helping to remove debris from the sparking gap (Fig. 14b). In deeper region, as shown in Fig. 15, cavitation bubbles are also observed. Due to the buoyancy force, these cavitation bubbles rise towards the surface region, which is helpful to carry out the debris from the machining gap.

Cavitation phenomenon is strongly related to acoustic pressure  $P_{ac}$ , as determined in Eq. (1) [26]:

$$P_{ac} = 2\pi f_{us} A \rho c \quad (1)$$

where  $f_{us}$  is oscillations frequency (Hz),  $\rho$  dielectric fluid density ( $\text{kg}/\text{m}^3$ ),  $c$  sound velocity in dielectric (m/s) and  $A$  vibration amplitude (m). According to Ghiculescu et al. [27], to produce cavitation,  $P_{ac}$  must be greater than a cavitation threshold. The cavitation threshold mainly depends on the ambient pressure (1 bar) [28]. In this study,  $f_{us} = 20$  kHz,  $A = 10$   $\mu\text{m}$ ,  $\rho = 767$   $\text{kg}/\text{m}^3$  and  $c = 1320$  m/s. Under these conditions, the acoustic pressure  $P_{ac}$  is 1.27 MPa. From this result, we can see that the acoustic pressure is far greater than the ambient pressure. In other words, the acoustic pressure is sufficiently high to cause cavitation bubbles in this study.

Normally, in a cavitation process, bubbles grow and collapse. However, in the present study, we found that cloud cavitation oscillating around the machining area instead of collapse. According to Suslick [21], cavity growth depends on the intensity of sound. In the case of low intensity ultrasound (20 kHz), the cavity size will not grow and collapse as the one induced by high intensity ultrasound. Instead, these cavities will simply oscillate, often nonlinearly, for many cycles of expansion and compression. A cloud cavitation will be formed when these stable cavities gathered at equilibrium position, i.e., the pressure nodes level [29]. In a cloud cavitation, the nonlinear bubble dynamics produces nonlinear interactive effects which cause cascading of fluctuation energy [30,31]. Due to the fluctuating energy in the dielectric fluid, the debris might be flushed out from the gap.

The schematic model for debris removal through the cavitation assisted micro-EDM of a deep micro-hole is shown in Fig. 16. By using ultrasonic vibration, two effects might be expected. One is the vibration-induced stirring effect which is helpful to uniformly distribute the carbon nanofibers in the dielectric fluid. The other is the vibration-induced cloud cavitation bubbles which help

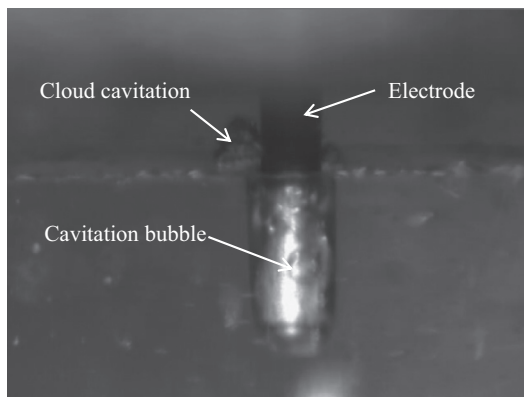


Fig. 15. High speed camera observation of deep region when using ultrasonic cavitation.

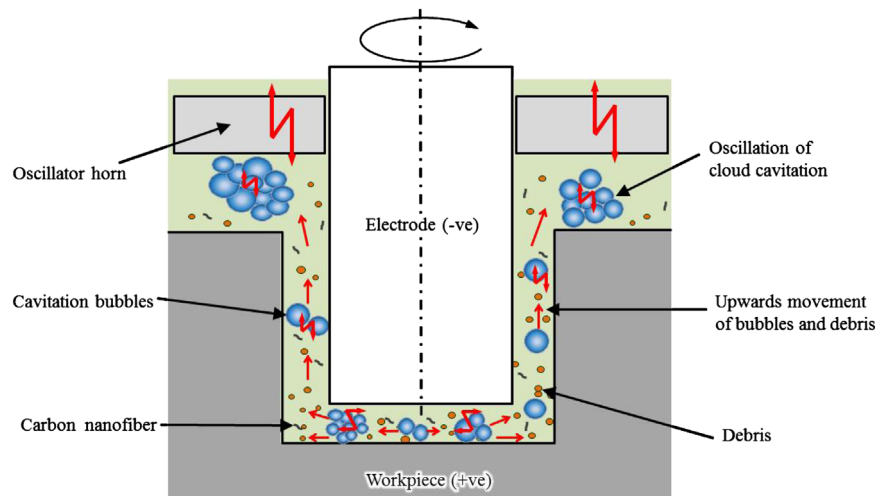


Fig. 16. Schematic model for debris removal through the cavitation assisted micro-EDM of a deep micro-hole.

to flush out the debris. Due to these two effects, short circuit and unstable machining can be prevented, leading to significant improvement in EDM performance. From this meaning, the proposed hybrid micro-EDM method in this study provides the possibility for high-efficiency precision manufacturing of micro-structures on ultra-hard RB-SiC ceramic materials.

## 5. Conclusions

Ultrasonic cavitation assisted micro-EDM of deep holes was proposed and verified by machining tests of RB-SiC. Effects of ultrasonic vibration on hole depth, hole geometry, surface topography, process stability and tool material deposition were experimentally investigated. The main conclusions are summarized as follows:

1. Ultrasonic vibration of dielectric fluid using a probe-type vibrator is effective to improve the micro-EDM performance including material removal rate, maximum machining depth, surface topography, hole geometry, and process stability.
2. The effect of ultrasonic vibration is significant only when carbon nanofibers are mixed in the dielectric fluid. Without carbon nanofibers, the effect of ultrasonic cavitation alone is insignificant.
3. Vibration amplitude strongly affects the depth of machined micro hole. The maximum depth of micro hole was achieved at vibration amplitude of 10  $\mu\text{m}$ .
4. Ultrasonic vibration induces two major effects. One is stirring effect which is helpful to uniformly distribute the carbon nanofibers in the dielectric fluid. The other is the cloud cavitation bubbles which help to flush out the debris.
5. Cloud cavitation is generated not only in surface region, but also in deep region. It is the upward flow and oscillation of cavitation bubbles that help to remove the debris.
6. Micro-holes having ten micron level diameters and high aspect ratios ( $> 20$ ) were successfully fabricated on reaction-bonded silicon carbide in a few minutes.

## Acknowledgments

The authors would like to thank Taga Denki Co., Ltd., Japan for providing the ultrasonic cavitation equipment. Professor Hitoshi Soyama of Department of Nanomechanics, Tohoku University is gratefully acknowledged for his valuable comments and advices. One of the authors P.J. Liew acknowledges the financial support from Ministry of Higher Education (MoHE) and Universiti Teknikal Malaysia Melaka (UTeM) for her Ph.D. scholarship.

## References

- [1] O.A. Abu Zeid, On the effect of electrodischarge machining parameters on the fatigue life of AISI D6 tool steel, *Journal of Materials Processing Technology* 68 (1) (1997) 27–32.
- [2] M.P. Jahan, Y.S. Wong, M. Rahman, A study on the fine-finish die-sinking micro-EDM of tungsten carbide using different electrode materials, *Journal of Materials Processing Technology* 209 (2009) 3956–3967.
- [3] D. Reynaerts, W. Meeusen, H.V. Brussel, Machining of three-dimensional microstructures in silicon by electro-discharge machining, *Sensors and Actuators A* 67 (1998) 159–165.
- [4] B. Ekmekci, A. Sayar, Debris and consequences in micro electric discharge machining of micro-holes, *International Journal of Machine Tools and Manufacture* 65 (2013) 58–67.
- [5] S.H. Yeo, L.K. Tan, Effects of ultrasonic vibrations in micro electro-discharge machining of microholes, *Journal of Micromechanics and Microengineering* 9 (1999) 345–352.
- [6] E. Bamberg, S. Heamawanachai, Orbital electrode actuation to improve efficiency of drilling micro-holes by micro-EDM, *Journal of Materials Processing Technology* 209 (2009) 1826–1834.
- [7] Y.S. Wong, L.C. Lim, L.C. Lee, Effects of flushing on electro-discharge machined surfaces, *Journal of Materials Processing Technology* 48 (1995) 299–305.
- [8] T. Masuzawa, X. Cui, N. Taniguchi, Improved jet flushing for EDM, *Annals of the CIRP* 41 (1) (1992) 239–242.
- [9] Z.Y. Yu, K.P. Rajurkar, H. Shen, High aspect ratio and complex shaped blind micro-holes by micro-EDM, *CIRP Annals – Manufacturing Technology* 51 (1) (2002) 359–362.
- [10] C. Gao, Z. Liu, A study of ultrasonically aided micro-electrical-discharge machining by the application of workpiece vibration, *Journal of Materials Processing Technology* 139 (2003) 226–228.
- [11] B.H. Yan, M.D. Chen, Effect of ultrasonic vibration on electrical discharge machining characteristics of Ti–6Al–4V alloy, *Journal of Japan Institute of Light Metals* 44 (5) (1994) 281–285.
- [12] H. Huang, H. Zhang, L. Zhou, H.Y. Zheng, Ultrasonic vibration assisted electro-discharge machining of microholes in nitinol, *Journal of Micromechanics and Microengineering* 13 (2003) 693–700.
- [13] W. Zhao, Z. Wang, S. Di, G. Chi, H. Wei, Ultrasonic and electric discharge machining to deep and small hole on titanium alloy, *Journal of Materials Processing Technology* 120 (2002) 101–106.
- [14] H. Tong, Y. Li, Y. Wang, Experimental research on vibration assisted EDM of micro-structures with non-circular cross-section, *Journal of Materials Processing Technology* 208 (2008) 289–298.
- [15] Z.Y. Yu, Y. Zhang, J. Li, J. Luan, F. Zhao, D. Guo, High aspect ratio micro-hole drilling aided with ultrasonic vibration and planetary movement of electrode by micro-EDM, *CIRP Annals – Manufacturing Technology* 58 (2009) 213–216.
- [16] J.C. Hung, J.K. Lin, B.H. Yan, H.S. Liu, P.H. Ho, Using a helical micro-tool in micro-EDM combined with ultrasonic vibration for micro-hole machining, *Journal of Micromechanics and Microengineering* 16 (2006) 2705–2713.
- [17] G.S. Prihandana, M. Mahardika, M. Hamdi, Y.S. Wong, K. Mitsui, Effect of micro-powder suspension and ultrasonic vibration of dielectric fluid in micro-EDM processes-Taguchi approach, *International Journal of Machine Tools and Manufacture* 49 (2009) 1035–1041.
- [18] H. Ogawa, S. Hamada, T. Aoyama, Ultrasonic cavitation assisted EDM of CFRP, *Electrical Machining Technology* 36 (112) (2012) 21–26. (in Japanese).
- [19] P.J. Liew, J. Yan, T. Kuriyagawa, Carbon nanofiber assisted micro electro discharge machining of reaction-bonded silicon carbide, *Journal of Materials Processing Technology* 213 (7) (2013) 1076–1087.
- [20] P.J. Liew, J. Yan, T. Kuriyagawa, Experimental investigation on material migration phenomena in micro-EDM of reaction-bonded silicon carbide, *Applied Surface Science* 276 (2013) 731–743.
- [21] K.S. Suslick, The chemical effects of ultrasound, *Scientific American* 260 (1989) 80–86.
- [22] J. Wang, F. Han, G. Cheng, F. Zhao, Debris and bubble movements during electrical discharge machining, *International Journal of Machine Tools and Manufacture* 58 (2012) 11–18.
- [23] Technical data provided by the manufacturer, available from (<http://www.tagaele.com/industrial/sc450.html>).
- [24] Y.F. Chen, Y.C. Lin, Surface modifications of Al–Zn–Mg alloy using combined EDM with ultrasonic machining and addition of TiC particles into the dielectric, *Journal of Materials Processing Technology* 209 (2009) 4343–4350.
- [25] T. Endo, T. Tsujimoto, K. Mitsui, Study of vibration-assisted micro-EDM-The effect of vibration on machining time and stability of discharge, *Precision Engineering* 32 (2008) 269–277.
- [26] D. Ghiculescu, N.I. Marinescu, G. Jitianu, G. Seritan, On precision improvement by ultrasonics-aided electrodischarge machining, *Estonian Journal of Engineering* 15 (1) (2009) 24–33.
- [27] D. Ghiculescu, N.I. Marinescu, S. Nanu, Influence of macro and microgeometry machined surface on ultrasonic aided electrodischarge machining, *International Journal of Material Forming* 1 (2008) 1339–1342.
- [28] J.E. Barger, Thresholds of acoustic cavitation in water, *Technical Memorandum* 57 (1964) 1–174.
- [29] J.L. Laborde, C. Bouyer, J.P. Caltagirone, A. Gerard, Acoustic bubble cavitation at low frequencies, *Ultrasonics* 36 (1998) 589–594.
- [30] S. Kumar, C.E. Brennen, Nonlinear effects in the dynamics of clouds of bubbles, *Journal of the Acoustical Society of America* 89 (1991) 707–714.
- [31] C.E. Brennen, *Cavitation and Bubble Dynamics*, Oxford University Press, Inc, New York, 1995.