1. Generation of bubble

Electrode materials and dielectric liquid are evaporated, molecules are dissociated, and atoms are ionized, resulting in a rapid expansion of the bubble. Since the expansion is restricted by the inertia and viscosity of the dielectric liquid, the pressure inside the bubble becomes extremely high and the boundary between the bubble and liquid expands with the velocity of several tens m/s [1, 2]. After the end of the discharge duration, ions and electrons are recombined and the dielectric breakdown strength is recovered. The evaporated atoms and molecules are solidified or condensed to form debris particles or dielectric liquid, but gases such as hydrogen and methane which are generated by the dissociation of the working oil are left to form a bubble.

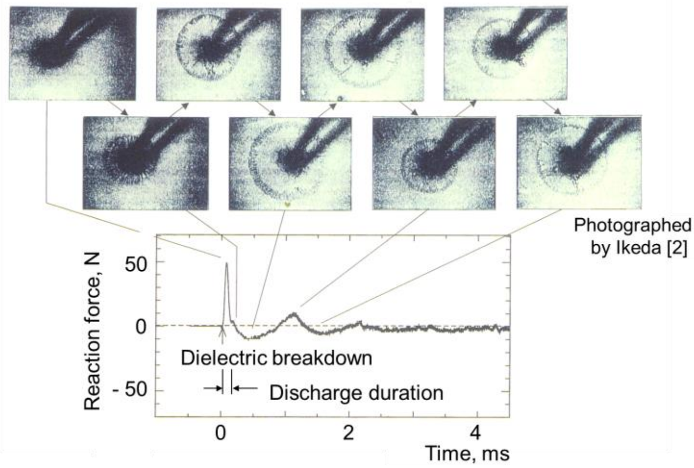

Figure 1: Oscillation of bubble observed by Ikeda [2] and reaction force measured by Split Hopkinson Bar method (i_e 30A, t_e 150μs, gap width 0.15mm, anode: copper φ20mm, cathode: steel φ20mm).

2. Oscillation of bubble

Photos in Figure 1 taken by Ikeda [2] show the oscillation of the bubble generated by a single pulse discharge in a gap between parallel plane electrodes. The diameter of the bubble reaches several millimeters, several tens of times larger than the gap width. Figure 2 shows side views of the bubbles generated by a single pulse discharge in deionized water and EDM oil. In the analogy to a mass and spring oscillation system, the bubble and dielectric liquid are analogous to the spring and mass, respectively. Due to discharge, gas molecules, atoms, ions and electrons are generated, being compressed in a small volume at the discharge spot. Starting from this initial condition, the dielectric liquid is accelerated radially away from the discharge spot and the potential energy of the bubble is transferred to the kinetic energy of the liquid. At the moment the pressure inside the bubble equals the atmospheric pressure, the kinetic energy peaks. Hence, the bubble continues expanding. The diameter of the bubble reaches the maximum when all the kinetic energy is transferred to the potential energy of the bubble. The bubble hereafter starts contracting until it is compressed to the initial diameter. In reality, the viscosity of the dielectric liquid causes damping in the oscillation. Figure 3 shows the change in the bubble diameter with passage of time measured from the side view of the bubble oscillation. It is noted that the bubble diameters in deionized water and EDM oil are almost the same.

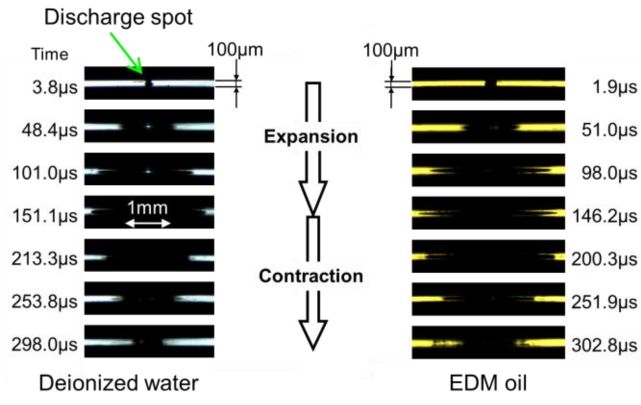

Figure 2: Side view of bubble oscillation (i_e: 20A, t_e: 100μs, gap width: 0.1mm, anode: Cu φ5mm, cathode: Cu φ5mm)

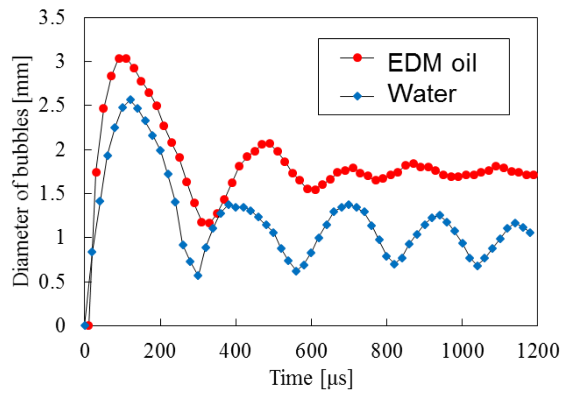

Figure 3: Diameter of bubble generated by single pulse discharge (Discharge current: 20A, discharge duration: 50μs)

3. Force applied to electrodes

Reaction force is applied to the electrodes due to the expansion and contraction of the bubble. Figure 4 shows a model to calculate the bubble oscillation in the gap between parallel plane electrodes [1]. The model illustrates a case that a bubble with a high pressure is generated at the center of the gap between cylindrical electrodes. The reaction force applied to the tool electrode can be calculated by integrating both the pressure in the bubble and that in dielectric liquid over the working surface [3]. The reaction force in Figure 1 was measured by Kunieda et al. [4] using the Split Hopkinson Bar method [5], with which the influence of the natural frequency of the measurement system was successfully eliminated. At the initial state in which the bubble is compressed, the force indicates the highest peak. With the expansion of the bubble, the force decreases according to the decrease of the bubble pressure. The force even becomes negative because the bubble continues to expand even after the bubble pressure falls below the atmospheric pressure due to the inertia of the dielectric liquid which is moving radially away from the discharge spot. When the diameter of the bubble reaches the maximum, the absolute value of the negative force becomes maximum. Then, the bubble starts contracting, and the force increases showing a damping oscillation. The period of oscillation is more than ten times longer than the discharge duration.

Figure 5 shows a simulation result of the reaction force calculated using the model in Figure 4. Since the acceleration is very high at the time of the dielectric breakdown, the inertia term is considerably more dominant than the viscosity term in the fluid-dynamic equations of the dielectric liquid. Hence, it should be sufficient to consider only the one-dimensional axisymmetric model, ignoring the viscosity. As a boundary condition, the periphery of the gap is considered to be at the atmospheric pressure. It was also assumed that the bubble expansion and compression is adiabatic and the dielectric liquid is incompressible.

Since the natural frequencies of EDM machine structures are much lower than the frequency components included in the reaction force waveform, the gap width cannot respond to the change in the force. Furthermore, the reaction force in a series of pulse discharges decreases with time while the working gap fills with bubbles generated by each discharge [3, 4]. Hence influence of the force caused by each pulse discharge is negligibly small in sinking EDM. However, it causes vibration and deflection of electrodes in the cases of wire EDM and micro EDM.

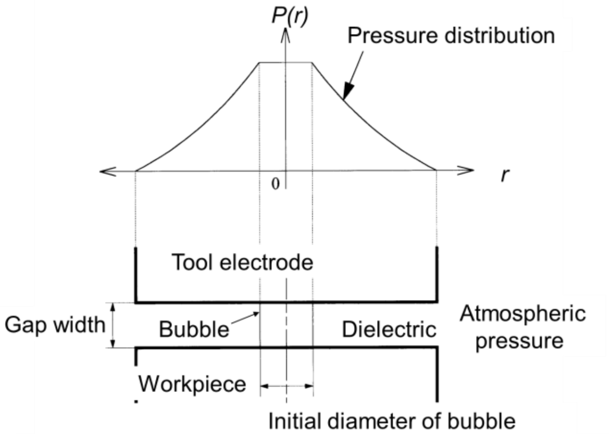

Figure 4: Pressure distribution in bubble generated by single pulse discharge in gap filled with dielectric liquid.

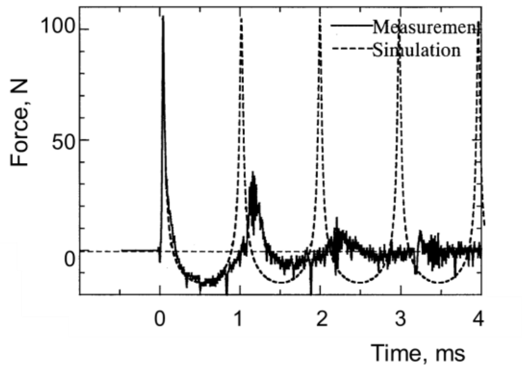

Figure 5: Calculated force acting on electrodes due to bubble oscillation (i_e: 45A, t_e: 150μs, gap width: 150μm, EDM oil)

4. Volume of bubble generated by single pulse discharge

The bubble generated by a single pulse discharge is composed of vapors of dielectric liquid and electrodes, and molecules and atoms which are generated by cracking the molecules of the dielectric liquid. Therefore, it is considered that the volume of the bubble immediately after discharge is greater than that measured long time after discharge. The volume of the bubble at atmospheric pressure immediately after discharge can be obtained from Figures 3 and 5. First, the moment when the pressure in the bubble equals the atmospheric pressure can be obtained from Figure 3 because the force becomes zero at the moment. Then the diameter of the bubble at the same moment can be obtained from Figure 5. Thus the volume of bubbles generated immediately after discharge in deionized water and EDM oil were obtained as shown in Figure 6. In the bubbles which can be collected by displacement method in the dielectric liquid tub of the machine tool during the process, the vapors are condensed and cracked atoms are recombined. Hence, the volume of the bubble long after discharge should be smaller than that immediately after discharge. The volume of the bubble long after discharge can be obtained by measuring the volume of the bubbles collected using the displacement method during machining and dividing the volume with the total number of discharge. The results were compared with the volumes of bubbles generated immediately after discharge in Figure 6. It is found that the volume of bubble contracted to one fourth at most after discharge in EDM oil, while contraction was significantly large for discharge in deionized water.

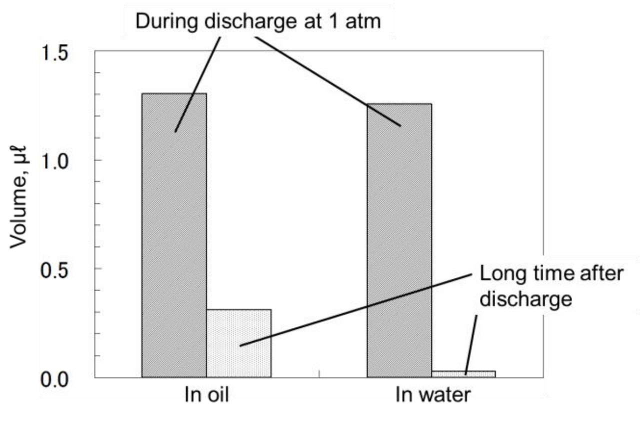

Figure 6: Comparison of bubble volume immediately and long time after discharge (i_e:20A, t_e:100μs, gap width:100μm)

5. Components of bubbles

Gas components of the bubbles sampled by the displacement method were analyzed using gas chromatography. As shown in Figure 7, using an EDM oil as dielectric, more than 50% was hydrogen gas. Others were oxygen gas, nitrogen gas, and hydrocarbon gases such as methane, ethylene, and acetylene. Oxygen gas and nitrogen gas were generated because air was dissolved in the oil prior to machining. With increasing discharge energy, percentages of hydrogen gas, and hydrocarbon gases with smaller molecular weight increased due to dissociation of the dielectric molecules. Using deionized water, which is normally used in wire EDM, bubbles were composed of hydrogen gas, oxygen gas, and nitrogen gas as shown in Figure 8. Water vapor was negligibly small due to condensation. The ratio of oxygen gas to hydrogen gas was smaller than the ratio determined by stoichiometry due to oxidation in the gap. Percentage of hydrogen gas increased with increasing the discharge energy, whereas percentage of oxygen gas decreased. It was found from Figure 6 that volume of the bubble generated due to discharge in deionized water shrinks significantly while the bubble is coming out of the working gap. This is because hydrogen and oxygen which are generated due to dissociation in the discharge plasma are recombined and condensed to form water after discharge. In contrast, shrink of bubble is insignificant for sinking EDM using oil because hydrogen gas and hydrocarbon gases are stable in the gap where oxygen does not exist. Some publications showed higher removal rate of water-based dielectrics [6, 7]. This is partly because the recombination reaction between hydrogen and oxygen generates additional heat flux to the workpiece.

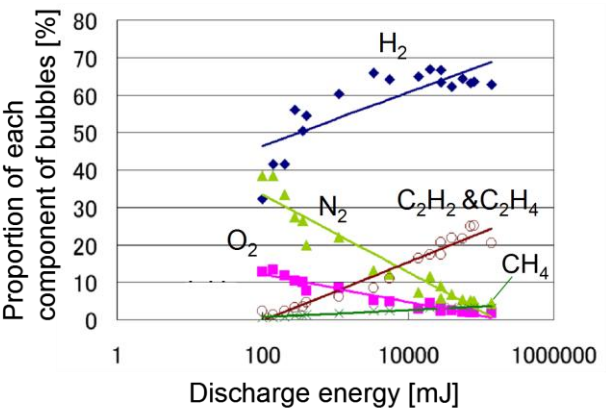

Figure 7: Components of bubbles generated in EDM oil

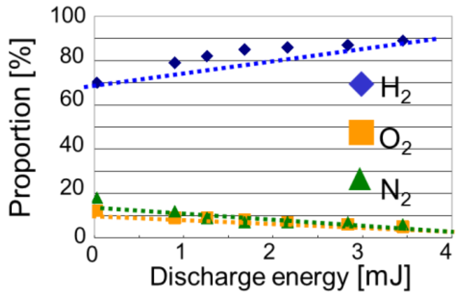

Figure 8: Components of bubbles generated in WEDM using deionized water (workpiece: steel)

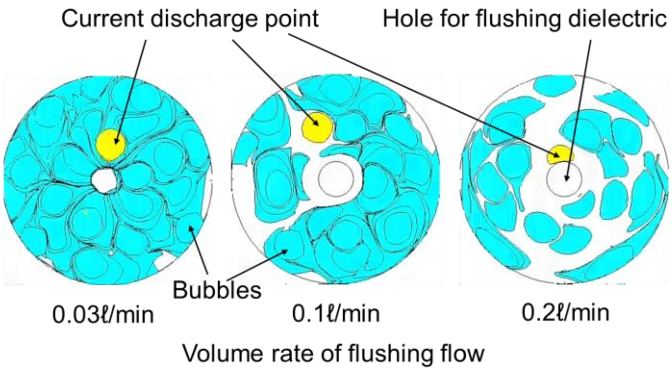

Figure 9: Bubbles in gap after 300 times of discharge (110ms after start of machining, i_e: 19A, t_e: 250μs, t_o: 50μs, diameter of copper electrode: 30mm)

6. Volume fraction of bubbles in gap

It is known that the working gap is mostly occupied by bubbles although the working gap is submerged in dielectric liquid [8]. Takeuchi and Kunieda [9] investigated the volume fraction of bubbles in the EDM gap during consecutive pulse discharges to understand the influence of the bubbles on the machining stability and material removal rate. Since optical observation of the EDM gap is difficult, generation and drift of bubbles in the gap were visualized based on theoretical analysis. The flow field in the gap was obtained by superposition of the dielectric flow due to the bubble generation at the discharge point and the radial flow of dielectric supplied from the center hole. Assuming that discharge occurs at random on the electrode surface except on the hole, the dielectric flow field was calculated, and an animation of the movement of bubbles was made as shown in Figure 9. In the steady state, the volume fraction reaches 85% and 52% when the volume rate of flushing flow is 0.1 and 0.2ℓ/min respectively. This indicates that the discharge in practical EDM processes is rather similar to the discharge in gas than that in the gap filled with dielectric. Hence, the relation of the debris size and crater diameter generated by discharge to the volume fraction of bubbles was investigated [9].

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