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ORIGINAL ARTICLE

Simulation model of debris and bubble movement in electrode jump of electrical discharge machining

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Abstract Electrode jump has a significant influence on the movement of debris and bubble in machining gap and further affects the stability of electrical discharge machining (EDM). Thus, an understanding on the mechanisms of debris and bubble movement in the electrode jump of EDM is important. However, these mechanisms have not been fully understood because it is difficult to observe and simulate the debris and bubble movement in the machining gap. This study proposed a three-dimensional model of flow field with liquid, gas, and solid phases for machining gap in the electrode jump of EDM. Based on this model, the mechanisms of debris and bubble movement in the machining gap in electrode jump were analyzed. Debris and bubble movement in machining gap in electrode jump was observed through experiments. The results showed that the proposed simulation model is feasible. The bubble in the bottom gap moves into the side gap because the flow field of the bottom gap is not centrosymmetric in the electrode jump. The vortexes of EDM oil in the bottom gap are generated during electrode jumping-up, which is the main factor that the debris mixes with the EDM oil. With the proper electrode jump height and speed, much debris and most of the bubbles are excluded from the bottom gap.

Keywords Debris · Bubble · Simulation · Movement · Electrical discharge machining (EDM)

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1 Introduction

Electrical discharge machining (EDM) has been widely used to manufacture dies and molds as well as aerospace, automotive, and surgical components. But, the accumulation of debris and bubble in machining gap results in poor performance of EDM [1–6]. As a measure of improving the machining condition of EDM, electrode jump was used in most of the EDM machine. It is necessary to understand the influence of electrode jump on the debris and bubble movement to obtain a good machining stability.

Cetin et al. [7] conducted the simulation of debris distribution in the electrode jump using the software Star-CD. The results showed that when the electrode jump height was low, the accumulation of debris was severe. Han et al. [8] established a two-dimensional model of flow field with liquid and solid phases for machining gap in the electrode jump. In order to simplify the simulation model, both the researches mentioned above have not considered the consecutive-pulse discharge process and have neglected the bubble in machining gap. Besides, these researches simplified the three-dimensional model of flow field of machining gap as two-dimensional, which was quite different from the actual situation. Wang et al. [9] observed the movement of debris and bubble in machining gap in electrode jump. Qualitative conclusions were drawn from these observations, but the quantitative analyzing of debris and bubble movement was difficult. Literature [10] conducted the research for analyzing the movement of debris and bubble in the electrode jump. But, the bubble was added into the machining gap by air blowing, which is quite different from the practical EDM conditions.

In this study, a three-dimensional and three-phase flow model of the machining gap in the electrode jump was established. Debris and bubble movement in this process was analyzed based on this model. Observation experiments were conducted to verify the simulation model.

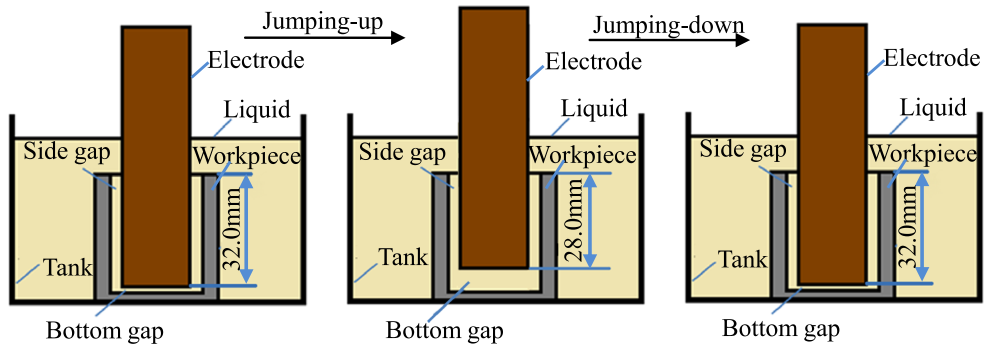


Fig. 1 Schematic diagram of the electrode jump motion

2 Simulation model of debris and bubble movement in electrode jump

The simulations in this study were conducted through the FLUENT software. The geometric model of the machining gap in the electrode jump was established firstly. Figure 1 showed the diagrammatic sketch of the electrode jump motion. To simplify the calculation, the flow field outside the machining gap was disregarded in this study. The geometric model of the machining gap at the beginning of the electrode jump should be established. In EDM, the consecutive-pulse discharge and electrode jump alternate. The electrode begins to jump when the period of consecutive-pulse discharge is over. So, the initial status of the machining gap in electrode jump was the same as the terminal status of that in consecutive-pulse discharge. In this study, the dimensions of the bottom gap and side gap were assumed to be constant in consecutive-pulse discharge. The machining conditions of the consecutive-pulse discharge were shown in Table 1. The dimensions of the bottom and side gap in consecutive-pulse discharge were measured through experiments. The diameters of the electrode and fabricated hole were measured; the difference between these diameters was the dimension of the side gap. As a result, the dimension of the side gap was 100 μm. The dimension of the bottom gap was determined through the following steps: (1) the *z*-coordinate was immediately recorded when discharge occurred between the electrode and workpiece, (2) the debris and EDM oil on the surface of the electrode and workpiece were cleared, and (3) the *z*-coordinate of the machine was recorded when the electrode came into contact with the workpiece. The difference between the two *z*-coordinates was the dimension of the bottom gap. As a result, the dimension of the bottom gap was 44.7 μm. Thus, a geometric model of the machining gap at the beginning of electrode jump was established (Fig. 2). The flow field domain was divided into a certain number of cells through the GAMBIT software and was imported into FLUENT.

In this research, the electrode jumped with the speed which was shown in Fig. 3. The maximum speed of the electrode was 1,900 mm/min and the electrode jump height was 4.0 mm. It can be seen from Fig. 1 that the dimension of the bottom gap kept changing in the electrode jump. In order to ensure the mesh adapts to the flow field deformation, Dynamic Mesh technique of FLUENT was used for automatically rediving the flow field mesh in the electrode jump.

The consecutive-pulse discharge model proposed in literature [11] was used to calculate the initial flow field of

Table 1 Processing conditions

Parameters	Values
Discharge voltage (V)	75
Discharge current (A)	9.8
Discharge duration (μs)	114
Pulse interval time (μs)	80
Electrode diameter (mm)	20.74
Electrode material	Copper
Workpiece material	Tool steel
Dielectric liquid	EDM oil

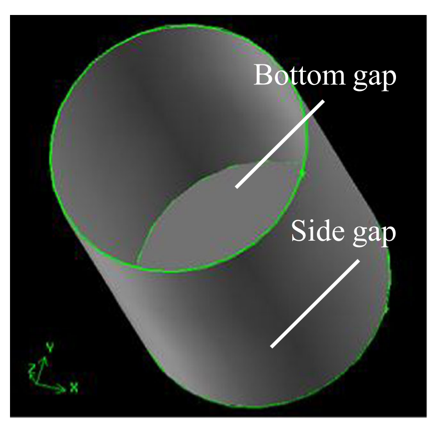


Fig. 2 The geometric model of the machining gap at the beginning of the electrode jump

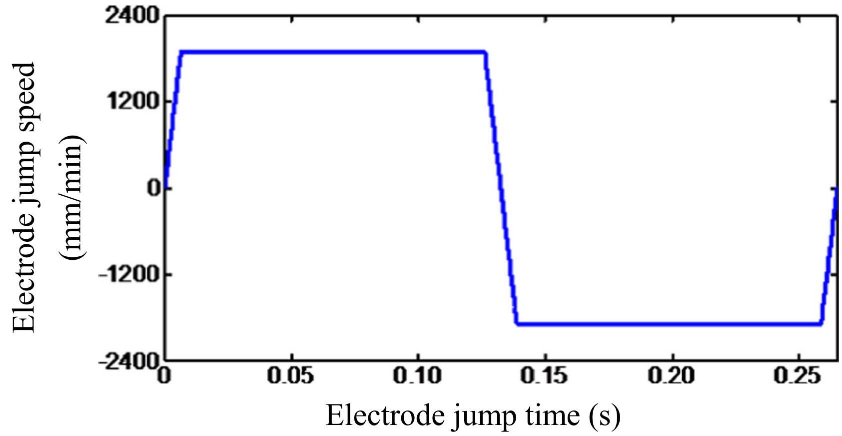


Fig. 3 The curve of the electrode jump speed

machining gap in the electrode jump. The time of one consecutive-pulse discharge process was set as 0.65 s. The simulation results at the moment 0.65 s were shown in Fig. 4. In Fig. 4a, the unit of the time was second; the left column of numerals corresponding to different colors represented the volume fraction of gas. For example, the region of which the number was "0" means that this region is full of EDM oil. In Fig. 4b, the unit of the time was second; the left column of numerals corresponding to different colors represented the accumulated moving time of the debris.

In order to confirm the flow type of the flow field of the machining gap (laminar flow or turbulent flow), the Reynolds number was calculated according to the following equation:

$$Re = \frac{\upsilon L}{\nu} \qquad (1)$$

where Re is the Reynolds number of the flow field, υ is the average speed of the fluid through the cross section of the machining gap, L is the characteristic length of the flow field, and ν is the kinematic viscosity of the fluid in the machining gap.

For the side gap, the characteristic length was constant 0.2 mm; ν was considered as the kinematic viscosity of the EDM oil (2.4×10^{-6} m^2/s); υ was considered as the speed of the EDM oil in the side gap, which can be calculated through the model shown in Fig. 5. Assume that the electrode jumped up from height 0 to h with the maximum speed $\upsilon_{\max}$ and the time consumption of this process is t. Then, the volume of the bottom gap will increase by ΔV_{gap} at the end of the process. The ΔV_{gap} was calculated as "$\pi\cdot r^2\cdot\upsilon_{\max}\cdot t$," where r is the radius of the electrode. According to the continuity of the fluid, the EDM oil with the volume of ΔV_{oil} will be simultaneously absorbed into the machining gap. The ΔV_{oil} was calculated as "$\pi\cdot(R^{2-}r^2)\cdot\upsilon\cdot t$," where R is the radius of the fabricated hole. Since ΔV_{gap} equals to ΔV_{oil}, the υ can be calculated and the result was 1.6341 m/s. Finally, the maximum Reynolds number of the side gap in electrode jump was calculated and the result was 136. This value is much smaller than the critical value of 2,300. Thus, the flow in the side gap in electrode jump is laminar flow.

For the bottom gap, the characteristic length was varying as the electrode jumped and its maximum value

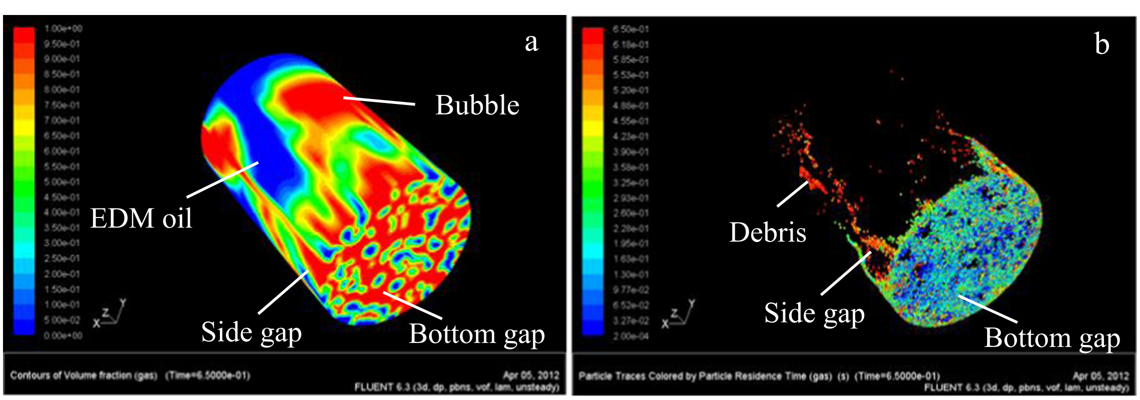


Fig. 4 Simulation results of the flow field at the beginning of the electrode jump

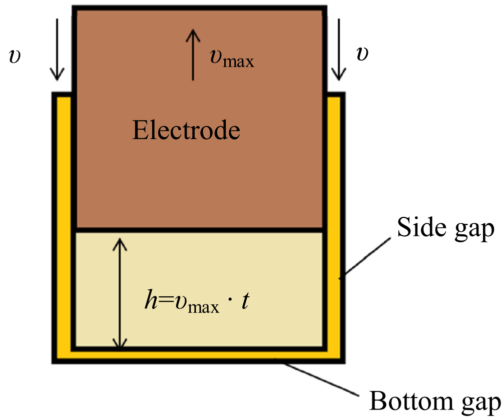


Fig. 5 Model for calculating the "*Re*" of the flow field of the side gap

was 4.0 mm; the fluid around the bottom gap had a tendency of moving towards the center of the bottom gap, resulting in the loss of the velocity of the fluid. So, the velocity of the fluid in the bottom gap should be much smaller than that in the side gap. Figure 6 showed the simulation result of the velocity distribution of the EDM oil in the machining gap in electrode jumping-up. The simulation assumed that the machining gap was full of EDM oil, and the flow type was laminar flow. In Fig. 6, the unit of the time was second, and the left column of numerals corresponding to different colors represented the velocity of the EDM oil. Figure 6 was the distribution of velocity of the EDM oil when the electrode moved to the height of 2.0 mm. At this moment, the speed of the electrode had reached the maximum value. It can be seen from Fig. 6 that the maximum velocity of the EDM oil in the bottom gap was 0.258 m/s. Take the characteristic length 2.0 mm and the velocity 0.258 m/s into the formula (1). As a result, the Reynolds number was 215, which was much smaller than the critical value of 2,300. Even when the

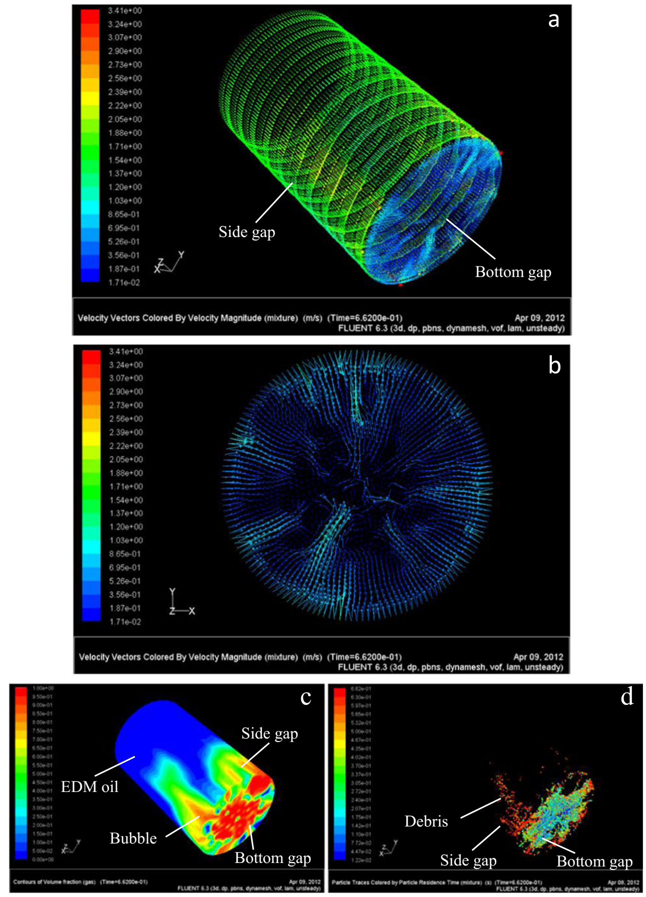


Fig. 7 Simulation result of bubble and debris movement (H_u= 0.2797 mm)

L got its maximum value 4.0 mm, the Reynolds number was still much smaller than the critical value. Thus, the flow in the bottom gap in the electrode jump was laminar flow.

The movement of EDM oil and bubble was calculated by the "volume of fluid model" of the software FLUENT.

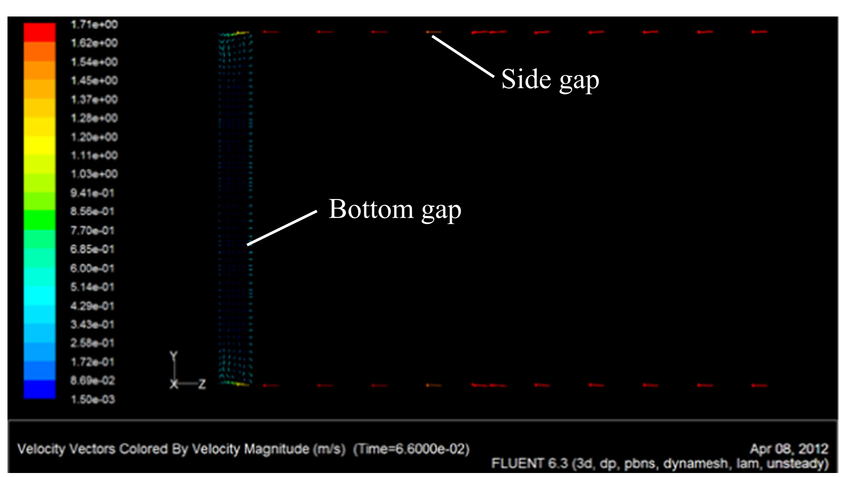


Fig. 6 Simulation result of the EDM oil velocity

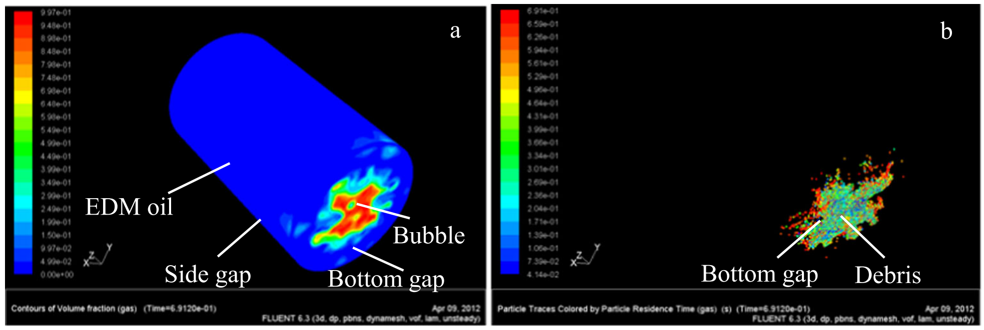


Fig. 8 Simulation result of bubble and debris movement (H_u=1.2 mm)

Simultaneously, the movement of the debris was calculated by the "discrete phase model" of the software FLUENT.

3 Simulation results of debris and bubble movement in electrode jump

The simulation results of the debris and bubble movement in the electrode jump is shown in Figs. 7, 8, 9, 10, 11, and 12. Figures 7–10 showed the debris and bubble movement in electrode jumping-up. The height of the electrode in electrode jumping-up was represented by "H_u." Figs. 7a, b showed the simulation result of the velocity of EDM oil and bubble when the H_u was 0.2797 mm. The unit of the time was second, and the left column of numerals corresponding to different colors represented the velocities of the EDM oil and bubble in the flow field. It can be seen from Fig. 7a that the EDM oil and bubble in the side gap moved towards the bottom gap. In order to clearly observe the EDM oil and bubble movement in the bottom gap, the top view of the flow field was given in Fig. 7b. It can be seen that the EDM oil and bubble had a tendency of moving towards the center of the bottom gap, but the velocity vector of the flow field in bottom gap was not centrosymmetric. With such velocity, the bubble and debris in the side gap moved into the bottom gap (Figs. 7c, d). Almost all of the bubble and debris in the side gap moved into the bottom gap when the H_u was 1.2 mm (Fig. 8). Figure 9a showed the top view of the machining gap; it can be seen that as the electrode continued jumping up, clean EDM oil moved into the bottom gap and most bubble joined into one large bubble; and EDM oil vortexes were generated at the corner of the machining gap (Fig. 9b) and stirred the debris in the bottom gap, resulting in the mixing of debris and EDM oil in the bottom gap (Fig. 9c). Figure 10 presented the top view of the machining gap; it can be seen that when the

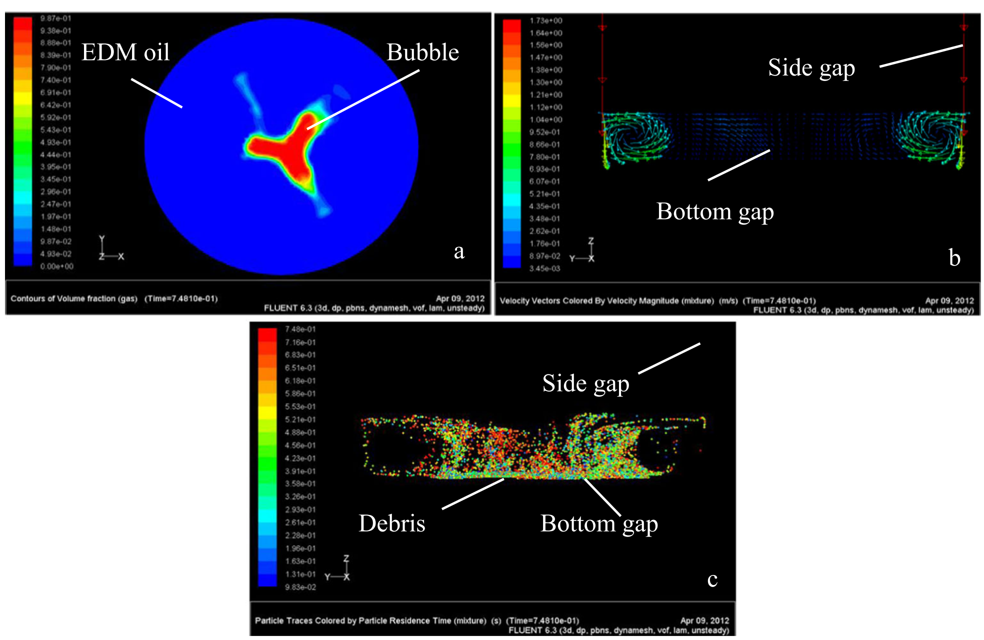


Fig. 9 Simulation result of bubble and debris movement (H_u=3.0 mm)

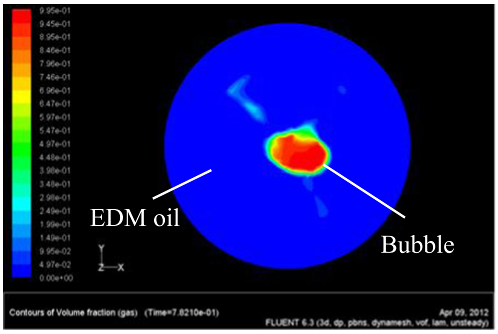


Fig. 10 The position of the bubble in the bottom gap (H_u=4.0 mm)

electrode reached the top position, the large bubble had moved away from the bottom gap center for a distance because the velocity of the EDM oil in the bottom gap was not centrosymmetric.

Figures 11 and 12 showed the debris and bubble movement in electrode jumping-down. The height of the electrode in electrode jumping-down was represented by "H_d." It can be seen from Fig. 11a that the large bubble kept moving away from the center of the bottom gap; some debris in the bottom gap began to move into the side gap (Fig. 11b). When the H_d was 0, almost all of the bubble in the bottom gap was excluded from the machining gap (Fig. 12a); most of the debris moved out of the bottom gap, and much of them moved outside of the machining gap (Fig. 12(b). Of debris, 88.03 % was excluded from the machining gap by the electrode jump.

4 Observation of debris and bubble movement in electrode jump

In order to verify the simulation model of debris and bubble movement in the electrode jump, observation experiments were conducted. The movement of debris and bubble in the side gap and bottom gap was observed respectively using the method proposed by literature [9]. The processing conditions of the consecutive-pulse discharge were the same as Table 1. The maximum speed of electrode was 1,900 mm/min.

Fig. 13 showed the debris and bubble movement in the side gap in the electrode jump. The electrode jump height was 4.0 mm. There were bubble and debris in the side gap at the beginning of electrode jump process (Fig. 13a); the bubble and debris in the side gap began moving into the bottom gap when the electrode jumped up (Fig. 13b); almost all of the bubble and debris in the side gap moved into the bottom gap when H_u was 1.0 mm (Fig. 13c); as the electrode continued jumping up, only clean EDM oil moved into the bottom gap (Fig. 13c, d). Then, the electrode began to jump down. It can

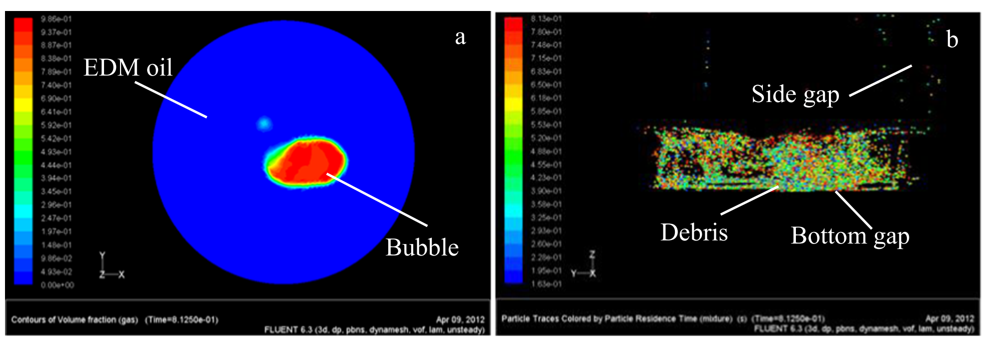


Fig. 11 Simulation result of bubble and debris movement (H_d=3.1503 mm)

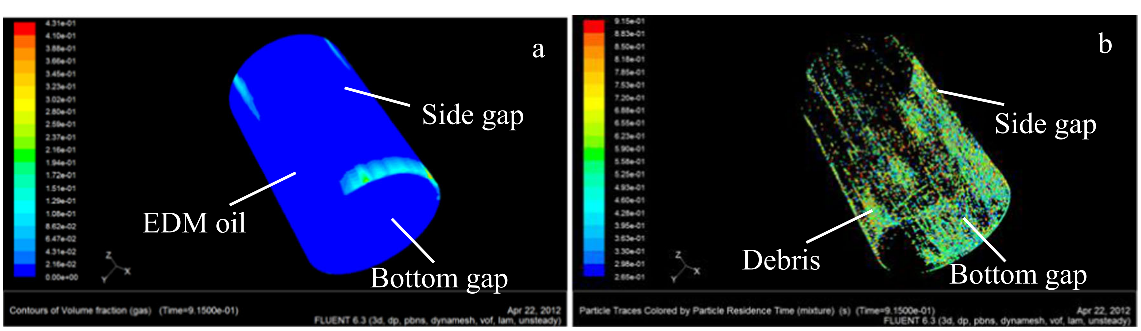
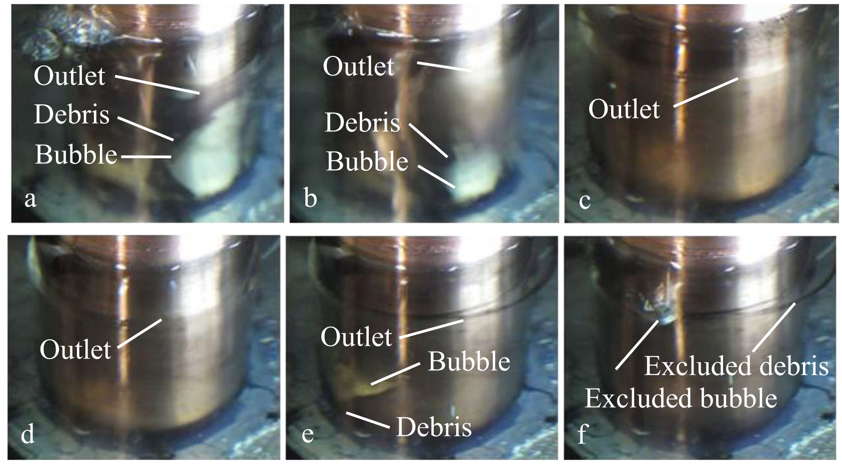


Fig. 12 Simulation result of bubble and debris movement (H_d=0 mm)

Fig. 13 Debris and bubble movement in the side gap in the electrode jump. (a) H_u=0 mm. (b) H_u=0.3 mm. (c) H_u=1.0 mm. (d) H_u=4.0 mm. (e) H_d=3.0 mm. (f) H_d=0 mm



be seen from Fig. 13e that some bubble and debris moved into the side gap. When the electrode returned to the original position, much debris and most of the bubble excluded from the machining gap (Fig. 13f).

Figure 14 showed the debris and bubble movement in the bottom gap in the electrode jump. The electrode jump height was 2.4 mm. The bubble moved towards the center of the bottom gap as the electrode jumped up (Fig. 14a, b); most of the bubble joined into a large bubble; the large bubble moved in the left direction; and the debris mixed with the EDM oil (Fig. 14c, d); the large bubble moved away from the bottom gap center and finally moved out of the machining gap, and much debris was exclude from the bottom gap (Fig. 14e, f).

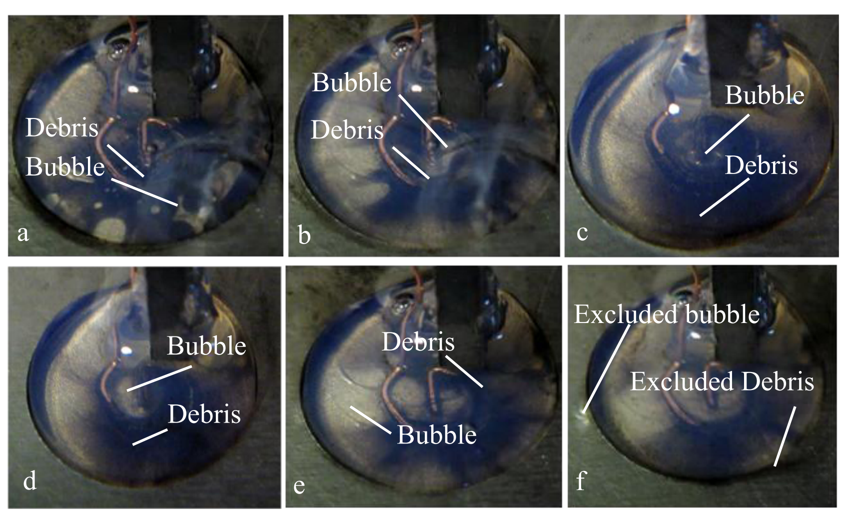
The observation experimental results showed consist with the simulation results on the debris and bubble movement. So, the simulation model of debris and bubble movement in the electrode jump was feasible.

5 Conclusions

The current research is an attempt of which the aim is to propose a simulation model of debris and bubble movement in the machining gap in the electrode jump. Observation experiments were conducted to verify the proposed model. Based on the simulated and experimental results with the processing conditions of the current research, the following conclusions were drawn:

1. The simulation results are in accordance with the experimental results on the movement of the debris and bubble in the machining gap, which demonstrates that the proposed simulation model is feasible.
2. In electrode jumping-up, bubbles in the side gap move into the bottom gap and join into a large bubble; the large bubble moves away from the bottom gap center because the velocity of the EDM oil

Fig. 14 Debris and bubble movements in bottom gap in electrode jump. (a) H_u=0 mm. (b) H_u=0.4 mm. (c) H_u=2.4 mm. (d) H_d=2.0 mm. (e) H_d=0.4 mm, (f) H_d=0 mm



in the bottom gap is not centrosymmetric. Then, in electrode jumping-down, the large bubble moves into the side gap and finally moves outside of machining gap following the EDM oil. Thus, with the proper electrode jump height and speed, little bubble is left in the bottom gap at the end of the electrode jump.

3. In electrode jumping-up, clean EDM oil outside the machining gap and the debris in the side gap are absorbed into the bottom gap. The debris mixes with the EDM oil in the bottom gap resulting in the decrease of the debris concentration. Then, in electrode jumping-down, much debris moved out of the bottom gap. Thus, with the proper electrode jump height and speed, a small part of debris is left in the bottom gap at the end of the electrode jump.

In order to elucidate the mechanism how the electrode jump height and speed affect the debris and bubble movement in the machining gap, a follow-up study should be conducted through combining the simulation model proposed by the current research with observation experiments.

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References

1. Suda T, Sata T (1974) Movement of conductive particles in EDM gap. J JSEME 7(14):19–28
2. Schumacher BM (1990) About the role of debris in the gap during electrical discharge machining. CIRP Ann Manuf Techn 39(1):197–199
3. Bommeli B, Frei C, Ratajski A (1979) On the influence of mechanical perturbation on the breakdown of a liquid dielectric. J Electrostat 7:123–144
4. Kunieda M, Yanatori K (1997) Study on debris movement in EDM gap. IJEM 2:43–49
5. Kunieda M, Kojima H, Kinoshita N (1990) On-line detection of EDM spark locations by multiple connection of branched electric wires. CIRP Ann Manuf Techn 39(1):171–174
6. Wang J, Han FZ, Zhao FL Improvement of EDM efficiency with a new adaptive control strategy. Int J Adv Manuf Technol 62(9-12): 1025-1040
7. CETIN S, OKADA A, UNO Y (2004) Effect of debris distribution on wall concavity in deep-hole EDM. JSME Int J Ser C 47(2):553–559
8. Han FZ, Zhang J, Cheng G, Takahito I (2010) Modeling of workpiece removal rate on EDM. Proceedings of the 16th International Symposium on Electromachining (ISEM XVI), Shanghai, China, 101-104
9. Wang J, Han FZ, Cheng G, Zhao FL (2012) Debris and bubble movements during electrical discharge machining. Int J Mach Tools Manuf 58:11–18
10. Pontelandolfo P, Haas P, Perez R (2013) Particle hydrodynamics of the electrical discharge machining process. Proceeding of the Seventeenth CIRP Conference on Electro Physical and Chemical Machining (ISEM XVII), Leuven, Belgium, 47-52
11. Wang J, Han FZ (2013) Simulation model of debris and bubble movement in consecutive-pulse discharge of electrical discharge machining. Int J Mach Tools Manuf 77:56–65