Effect of Tilting Jet Flushing Nozzle on Wire EDM Performance

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Abstract
Debris exclusion from the wire EDM gap has been conventionally done by jet flushing using nozzles but the debris stagnation area always presents near the wire with the conventional method. In this study, a new flushing method using tilting nozzle to wire running direction to reduce the debris stagnation in the kerf was proposed on the base of simulation results by computational fluid dynamics (CFD) analysis. The simulations and experiments clarified that the tilting jet flushing nozzle could decrease the debris stagnation area in the kerf and leads to smoother debris exclusion, resulting in higher removal rate. Furthermore, the wire deflection caused by hydrodynamic force due to the jet flushing was calculated by a structural analysis using the distributions of pressure acting on the wire surface by jet flushing flow obtained by the CFD analysis.

Key words: Wire EDM, tilting jet flushing nozzle, computational fluid dynamics, wire deflection

1. INTRODUCTION

Since the demand for fine precision machining has recently increased with the miniaturization of mechanical and electronic products, the gap control technology, the optimization of machining condition and the development of finer wire electrodes have been enhanced in wire EDM. In order to obtain high machining performance, better exclusion of debris from the machined kerf and reduction of wire vibration are essential. Debris stagnation in the gap results in secondary discharges and discharge concentrations, which leads to unstable machining performance, wire breakage, low machining rate, large machined surface roughness and low shape accuracy [1-3].

Our previous paper [8,9] on the flow fields in the wire EDMed kerf using a computational fluid dynamics (CFD) analysis showed that the debris stagnation area always presented near the wire electrode, and the conventional jet flushing method was not always effective, as shown in Fig. 1.

In order to reduce the debris stagnation area in the kerf for smooth debris exclusion, a new jet flushing method using tilting nozzle to wire running direction is proposed in this paper. Then, the effectiveness of this flushing method is verified by the wire EDM experiments using the proposed nozzle. Also, the deflection of wire electrode was calculated by a structural analysis using the distributions of pressure acting on the wire surface by jet flushing flow obtained by the CFD analysis. The jet flushing with a very high flow rate might be more effective for complex shapes and thick workpieces. However, such high flow rate would lead to greater wire vibration and lower shape accuracy. The effects of nozzle stand-off distance and flow rate from nozzles on the wire deflection were discussed. Furthermore, the wire deflections using normal nozzle and tilting nozzle were compared.

2. CFD ANALYSIS MODEL

Fig. 2 shows CFD analysis model for solving the flow field in wire EDM using the conventional jet flushing nozzle. This three dimensional model...
is based on an actual wire EDM for steel plate using deionized water under 1st cut conditions. The details of model conditions are listed in Table 1. In order to later calculate the wire electrode deflection due to jet flushing, the model includes the inside regions of upper and lower nozzles. On the upper and lower boundary surfaces, flow inlet circles of 6 mm in diameter were set for nozzle jet flushing, in which the flow rate was set to 6.0 L/min. The workpiece thickness is 10mm and the length of machined kerf is 10mm. The nozzle stand-off distance is set to 0.5mm. The wire electrode diameter is 200µm and the width of machined kerf is 250µm. Then the gap is 25µm.

The simulations presented in this study are processed by using a commercial software package of STAR-CCM+ Ver.5.02. This software operates by solving the governing differential equations of the flow physics by numerical means on a computational cell. The cell size adjacent to the wire electrode was small enough to simulate precisely, and the other parts were a little coarse for saving computational time. The governing equations are Navier-Stokes equations. The fluid flows, the debris tracks and the pressure distributions were calculated by a finite volume method as an unsteady turbulent flow with $K$-$\varepsilon$ model [10, 11].

A downward velocity of 10 mm/min was given to the wire circumference surface to realize the actual wire electrode running. A pressure boundary condition was set to a level of 10mm above the upper surface work piece. No slip condition was applied to the surfaces of workpiece, nozzle and wire electrode. The effects of impact force associated with sparks, bubbles behavior, electrostatic force acting on wire electrode, and wire vibration were neglected, since CFD analysis that considers these factors is impossible or very difficult under the current CFD techniques. However, the verification by the high-speed observation in our previous study proved that the CFD analysis results could well simulate the actual flow fields and debris movement in the gap without considering these effects [8].

### Table 1 CFD model conditions

| Parameter                          | Value        |
|------------------------------------|--------------|
| Workpiece thickness                | 10.0mm       |
| Machined kerf length $L_M$          | 10.0mm       |
| Wire diameter                       | 0.2mm        |
| Kerf width                         | 0.25mm       |
| Nozzle diameter                     | 6.0mm        |
| Wire running speed                 | 10.0m/min    |
| Stand-off distance                  | 0.5mm        |
| Flow rate                           | 6.0L/min     |
| Fluid density (Deionized water)    | 9.976 x 10^3 kg/m^3 |
| Viscosity (Deionized water)        | 8.887 x 10^-5 Pa*s |

3. **EFFECT OF TILTING NOZZLE**

It was clarified by our previous study that the stagnation area was always generated near wire electrode under any flushing conditions in conventional nozzle flushing [8]. In order to decrease the area, a new flushing method with a tilting nozzle was discussed. Fig. 3 shows the illustration and the photo of tilting nozzle. The hole tilts for the machining direction, and the angle is set to 30 degrees to change the flow field in the machined kerf.

Fig. 4 shows the analyzed flow fields in the kerf and the debris tracking simulations using the conventional normal nozzle and the tilting nozzle. For comparison, two flushing methods with the positive and negative tilting angles for wire feeding direction were discussed. These nozzles are named positive tilting nozzle and negative tilting nozzle, respectively. When the positive tilting nozzle is used, the stagnation area becomes very small near the middle of front wall in machined kerf. On the other hand, it is wider than that using the normal nozzle and negative tilting one. Also, it is noticed
that the debris tracks and distribution agree well with each flow field. These results mean that the flow field and the debris motion in the machined kerf can be changed by the nozzle flushing angle.

Fig. 5 shows the photographs of side wall in wire EDMed kerf by using a normal nozzle, positive tilting nozzle and negative one. A velocity map in the wire EDMed kerf simulated under the same jet flushing conditions is again shown for comparison. Dark marks can be clearly observed on any wire EDMed surfaces. It was confirmed with SEM observation that much debris and heat resolved carbon from dielectric kerosene fluid during machining adhered on the surface in the dark mark areas. This indicates that a flow with dense debris passes through the dark parts and/or much debris stagnates. When the positive tilting nozzle is used, the dark mark is concentrated in a small area at the middle near the wire electrode. Whereas, the area of dark mark is very wide in the case of the negative tilting nozzle. Furthermore, these dark marks on the wire EDMed surface agree well with stagnation area obtained by the CFD analysis. Therefore, the flow fields and the debris tracks analyzed by the CFD analysis can well express an actual debris movement. In the analysis, the wire vibration and deflection, electrostatic force acting on the wire and particles, bubble behavior and impact force associated with sparks were not taken into account. However, the analysis results almost agree with the experimental results, thus it is understood that these effects on the flow field and the debris tracks under jet flushing can be almost disregarded in the CFD analysis.

The reduction of debris stagnation area by the tilting jet nozzle would bring the improvement in the wire EDM characteristics. Therefore, the variations of removal rate with discharge current were investigated using three types of nozzle. The results are shown in Fig. 6. The setting discharge current was increased until the wire breakage occurred. Wire EDM with higher discharge current is possible when both tilting nozzles are used, compared with the case using normal nozzle. When the positive tilting nozzle is used, the stagnation area is decreased, which leads to more stable machining. As a result, higher discharge current can be applied and the removal rate can be improved. In the case of negative tilting nozzle, it is guessed that the generated debris would be dispensed widely because of wide expansion of vortex flow as shown above. Thus higher discharge current also can be applied even in the case of negative tilting nozzle. In this case, the kerf width increased with wide debris stagnation, as shown below. The increase in kerf width would decrease the removal rate, as compared with those in the cases of normal nozzle and positive tilting nozzle under the same discharge current condition.

Fig. 7 shows change in kerf width in the direction of workpiece thickness using three types of nozzle. The average clearance between the
electrode of φ200µm and the side wall surface in the case of positive tilting nozzle is smallest. This is because the debris stagnation area is concentrated to small area and the debris is smoothly. On the other hand, the clearance is the widest in the case of negative tilting nozzle, since the stagnation area is large and includes a lot of debris in the area. In addition, the straightness of the side wall is higher in the case of conventional normal nozzle. It is considered that the debris density around the wire electrode is large but uniform along to wire direction, as shown above. Therefore, uniform and low debris concentration around the wire electrode is ideal for wire EDM with higher shape accuracy.

4. HYDRODYNAMIC FORCE ACTING ON WIRE CAUSED BY JET FLUSHING

Fig. 8 shows flow field around the upper edge of workpiece using the normal nozzle analyzed by CFD. Two horizontal dashed lines shown in (a) side view are the edge of nozzle and the upper edge of workpiece. As can be seen from the figure, the direction of fluid flow from the nozzle is first vertical, but it inclines backward in the gap between workpiece upper surface and nozzle. This is because the machined kerf has not yet been formed in front of the wire. As shown in (a), the flow from nozzle in front of wire is blocked by the upper workpiece surface and turns horizontally, which makes horizontally radial flow centering around a point in front of wire, as shown in (b) . On the other hand, the flow turns to the machined kerf behind the wire.

There are two types of force acting on the wire with jet flushing of working fluid. One is pressure acting perpendicular to the wire surface, and another is shear stress acting parallel. Fig. 9 shows pressure distributions on the wire surface around the upper edge of workpiece using the normal nozzle. At the upper edge of workpiece, the pressure acting on the front surface is higher than that on the back surface of the wire. Also at the lower edge of workpiece, the situation is the same. Furthermore, the pressure acting on the wire inside the kerf is low, and the difference between pressures acting on the front and back wire surfaces is extremely small inside the kerf. These results show that the wire is forced backward concentratedly around the upper and lower edges of workpiece by the jet flushing. Shear stress distributions on the wire surface were also calculated and the value was approximately 1kPa at a maximum, which is much smaller than the maximum pressure acting on the wire of 225kPa. Therefore, the distribution of shear stress acting on the wire surface can be neglected in the simulation for the wire deflection discussed later.

In order to estimate the wire deflection due to the nozzle jet flushing, the distributions of pressure acting on the wire surface by the jet flushing flow obtained from the CFD analysis were given to the wire surface in the structural analysis model. The structural analysis of wire was done by using a commercial program of ANSYS Rev.14.0. The wire electrode material is assumed hard brass, and the wire is constrained in x-y directions at the upper and lower wire ends as the wire is actually constrained in x-y directions.
supported with upper and lower wire guides. Wire tension was realized by giving vertical tensile load at the both ends of wire. The structural analysis conditions are listed in Table 2. The wire tension was fixed to 12N in the following. The model was divided into sufficiently small computational cells to simulate precisely. The wire deflections were calculated by a finite volume method.

Fig. 10 shows the wire deflections in upper half of the analyzed area using the normal nozzle when the nozzle stand-off distance is varied. The horizontal scale of the wire displacement is amplified to emphasize the differences with the nozzle stand-off distance. It is understood that the wire electrode is deflected backward under any nozzle stand-off distances. The displacement takes a maximum at the midpoint of wire, and it decreases with nozzle stand-off distance.

Fig. 11 shows the variations of maximum wire displacement with flow rate from nozzles under various nozzle stand-off distances. As shown in the figure, the wire displacement becomes larger as the nozzle stand-off distance is small. Also, it becomes larger with the flow rate of working fluid from nozzles. Therefore, small nozzle stand-off distance and high flow rate from nozzles lead to large wire deflection and vibration, although such jet flushing conditions are more effective for smooth exclusion of debris and bubbles from the discharge gap. Therefore, for high performance wire EDM the balance between them is important.

In order to verify the accuracy of CFD and structural simulations of wire deflection, an actual wire deflection caused by the hydrodynamic force with jet flushing was observed and measured. The observation model is shown in Fig.12. The workpiece thickness is as thick as 150mm and the wire tension is as low as 1.0N to obviously observe the wire deflection. For observing the wire deflection, a small notch was first machined at the middle of workpiece, as shown in the figure. Next, the kerf of 10.0mm in length was wire-EDMed under higher wire tension, and the wire was stopped at the edge of the notch. Then, the movement of wire was observed through the small notch by using a zoom video camera when the wire is subjected to jet flushing.

Two photographs are the images inside the notch with and without jet flushing. In the photographs, the right side black area is the shadow of wire. As can be seen from the photographs, the difference in positions between wire front lines is

| Table 2 Structural analysis conditions |
|-------------------------------|-------------------|
| Wire                          | Hard brass        |
| Diameter                      | 0.2mm             |
| Length                        | 27mm (L)=6.5mm    |
| Wire tension                  | 12N               |
| Density                       | 8.4g/cm³          |
| Young’s modulus               | 106GPa            |
| Poisson ratio                 | 0.35              |

Fig. 10 Difference in wire deflection with nozzle stand-off distance using normal nozzle

Fig. 11 Variations of wire deflection with flow rate from nozzle for various nozzle stand-off distances using normal nozzle

Fig. 12 Observation of wire deflection caused by hydrodynamic force with jet flushing
about 86µm, while the wire deflection simulated by the CFD and structural analysis under the same flushing condition is 105µm. With the backward wire deflection, the flow field and pressure field around the wire changes in the observation model, which would leads to small decrease in the wire deflection. Considering this factor, it can be judged that the simulations in the present paper well expresses actual wire deflection.

The wire deflections using tilting nozzles calculated by CFD analysis and structural analysis are shown in Fig.13. The wire deflection is smaller in the case of positive tilting nozzle, compared with the normal nozzle and negative tilting one. It was confirmed that a forward force was newly generated inside the nozzle and in the gap between the nozzle and workpiece by the jet flushing with the positive tilting nozzle, separately from the concentrated backward force at the upper and lower edges of workpiece shown above. The both forces are balanced and the wire deflection consequently becomes very small, which is one of the reasons for the decrease in average kerf width by the positive tilting nozzle shown in Fig. 7, as well as the decrease in the debris stagnation area.

5. CONCLUSIONS

1) The debris stagnation in the machined kerf is limited to a small area and debris exclusion becomes smooth by using a positive tilting jet flushing nozzle, which enable the machining with high discharge current and high removal rate.

2) When the conventional jet flushing method using nozzles is applied, the wire electrode is subjected to a backward concentric force at the upper and lower edges of workpiece.

3) Smaller nozzle stand-off distance and high flow rate from nozzles lead to large wire deflection and vibration, although such jet flushing conditions are more effective for smooth exclusion of debris and bubbles from the discharge gap.

4) The wire deflection in the case of jet flushing with a positive tilting nozzle is smaller than that with a normal nozzle.

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