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Analysis of electromagnetic force in wire-EDM

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ABSTRACT

This paper clarifies the mechanism of how electromagnetic force applied to the wire electrode in wire electrical discharge machining (wire-EDM) is generated. This electromagnetic force is caused not only by DC component but also by AC components of the discharge current supplied to the wire. We therefore developed and used a two-dimensional finite element method (FEM) program to analyze the electromagnetic field taking into account electromagnetic induction. Assuming that trapezoidal pulse current is supplied to the wire, distributions of the current density and magnetic flux density were analyzed and changes in the electromagnetic force applied to the wire were calculated. Wire movement when the electromagnetic force alone was applied to the wire was also calculated. The calculated wire movement agreed with the measured wire movement when pulse current actually used in WEDM was supplied to the wire, clarifying the mechanism of electromagnetic force generation.

1. Introduction

In wire-EDM (WEDM), four kinds of forces are applied to the wire electrode [1,2]: discharge reaction force caused by rapid expansion of a dielectric fluid bubble at the discharge spot during discharge duration, electrostatic force when open voltage is applied between the wire and workpiece during ignition delay time, electromagnetic force caused by discharge current flowing through the wire, arc column, and workpiece during discharge duration, and hydrodynamic force generated by the flow of dielectric fluid. These forces cause vibration and deflection of the wire electrode, thereby lowering machining accuracy, speed, and stability [2,3]. On the other hand, Obara et al. [4], Han et al. [5], and Tomura et al. [6] developed programs for WEDM simulation. The simulation is based on the repetition of the following routine; calculation of wire vibration considering the forces applied to the wire, determination of the discharge location considering the gap width between the wire and workpiece, and removal of workpiece at the discharge location. Correct values therefore need to be obtained for these forces applied to the wire for accurate simulation.

Obara et al. [7] and Yamada et al. [8,9] obtained the discharge reaction force from solutions of inverse problems in which wire vibrations calculated using assumed values of the force were compared with measured ones. Han et al. [5] obtained the discharge reaction force in the same way from a solution of an inverse problem in which machined workpiece shapes simulated were compared with measured ones. Obara et al. [10] measured the change in the resultant force involving all the forces: discharge reaction force, electromagnetic force, and electrostatic force with various discharge frequencies. They then obtained the electrostatic force by extrapolating the resultant force to the limit of zero discharge frequency, because both the discharge reaction force and electromagnetic force are zero when discharge frequency is zero. Yamada et al. [8] analyzed the wire displacement caused by the electrostatic force when an open voltage was applied between the end of a thin plate and wire, and found that the analyzed results agreed with experiment. Han et al. [5] determined the relative permittivity in the gap where both dielectric liquid and bubbles exist during consecutive discharge using the inverse problem method and obtained the relation between the gap width and electrostatic force in actual working gaps. As for the influence of hydrodynamic force, Obara [11] analyzed the flow-field in a groove cut by WEDM and quantified the influence of the flow-field on the limit of wire breakage and machining speed.

Regarding electromagnetic force, Panschow [1] reported that the electromagnetic force caused by a consecutive pulse discharge current can be obtained by summation of the contributions from DC component and AC components in the Fourier transformation of the discharge current waveform. Electromagnetic force generated by DC component is attractive and Panschow calculated electromagnetic force using the principle of mirror image for workpiece materials with high permeability like mild steel. He obtained the electromagnetic forces generated by AC components from experiments measuring the wire deflection when a current with known frequency and amplitude was supplied to the wire. Since the wire was short-circuited with the workpiece, the electromagnetic force

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was measured independently without the influence of the discharge reaction force or electrostatic force. Thus, he found that when the workpiece was mild steel, the force was attractive with low frequency, but it changed to repulsive with increasing frequency. When the workpiece was brass, the force was always repulsive and increased with increasing frequency. Obara et al. [10] also found experimentally that the electromagnetic force is small and repulsive when workpiece is a paramagnetic material like copper, but it is attractive when workpiece is ferromagnetic like steel. Tomura and Kunieda [12] measured the wire movement caused only by the electromagnetic force. They also calculated the electromagnetic force by two-dimensional finite element method (FEM) analysis of electromagnetic field not taking into consideration electromagnetic induction, and analyzed the wire movement caused by the electromagnetic force calculated. They found that when permeability of workpiece was small like copper, the electromagnetic force due to DC component was negligible compared with the electromagnetic force generated by AC components. When permeability was large like steel, the electromagnetic force generated by DC component was dominant. However, there have been no reports on the calculation of the electromagnetic force taking into account electromagnetic induction due to AC components. Hence, in this research, a two-dimensional FEM analysis program taking into account electromagnetic induction was developed to clarify the mechanism of electromagnetic force in WEDM.

2. Mechanism of electromagnetic force generation

Fig. 1 shows the principle of electromagnetic force generated by DC component. It is assumed that a constant current flows through the brass wire along the wire axis toward the front as seen in Fig. 1. When the workpiece is copper, and the atmosphere is air or water, distribution of the magnetic flux density is axisymmetric and counterclockwise around the wire axis as shown in Fig. 1(a), because all the materials are paramagnetic and have significantly small permeability in the same order. The electromagnetic force can be calculated by vector product of current density and magnetic flux density. For this reason, the resultant electromagnetic force applied to the wire is insignificant because of the axisymmetric distribution of the magnetic flux and uniform current density. In contrast, when the workpiece is steel, the magnetic flux is not axisymmetrical around the wire axis as shown in Fig. 1(b) because permeability of the workpiece is significantly larger than the other materials. The magnetic flux density in the upper area is higher than that in the lower area of the cross-section of the wire. Hence, the resultant electromagnetic force applied to the wire is directed toward the workpiece. Tomura and Kunieda [12] calculated this electromagnetic force generated by DC component.

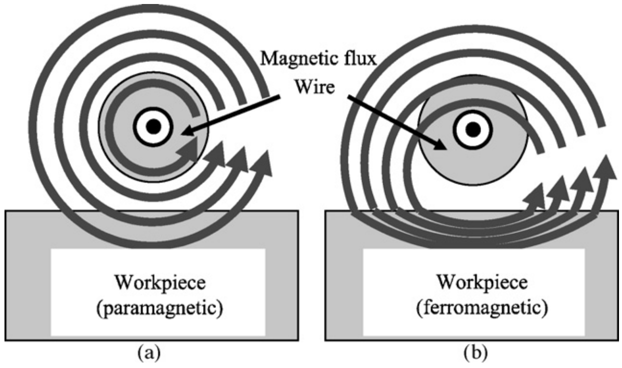

Fig. 1. Electromagnetic force generated by DC component.

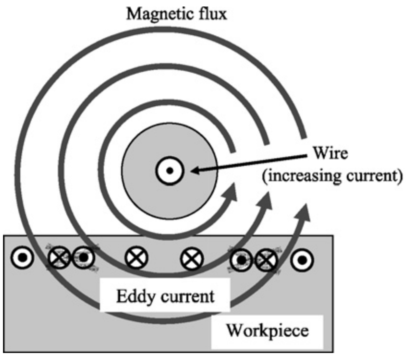

Fig. 2. Electromagnetic force generated by AC components.

Fig. 2 shows the principle of electromagnetic force generated by AC components. When current in the wire is rising, the magnetic flux density increases counterclockwise, generating an eddy current in the workpiece caused by electromagnetic induction. The direction of eddy current generated by each magnetic flux is determined so that the eddy current cancels the increase in the magnetic flux. Hence, the density of eddy current is highest under the wire, and it flows counterparallel to the current in the wire. Thus, the electromagnetic force caused by increasing current generates repulsive force. In the same way, when the current is falling, an eddy current is generated in the workpiece under the wire in the same direction as the current in the wire. Hence, the electromagnetic force applied to the wire is attractive when the current is falling. The above phenomena arise both in paramagnetic and ferromagnetic metals.

3. Calculation of electromagnetic force by electromagnetic field analysis

3.1. Electromagnetic field analysis using FEM

In the previous report [12], electromagnetic force generated by DC component alone was calculated. In this study, we developed an unsteady electromagnetic field analysis program taking into consideration electromagnetic induction using FEM [13,14]. This program can solve the following Poisson's equation considering electromagnetic induction in the two-dimensional field perpendicular to the wire axis.

$$\frac{\partial}{\partial x}\left(\frac{1}{\mu}\frac{\partial A_z}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{1}{\mu}\frac{\partial A_z}{\partial y}\right)=-J_0+\sigma\frac{\partial A_z}{\partial t}+\sigma\frac{\partial \phi}{\partial z}.$$

Here μ is permeability, A_z is Z-component of electromagnetic vector potential, ϕ is electric potential caused by electromagnetic induction, σ is conductivity, and J_0 is forced current density. In the case of a steady current flowing through a uniform conductor, the distribution of current density is uniform. Thus the forced current density J_0 is obtained by dividing the current supplied to the conductor form outside by the cross-section area of the conductor. $\sigma(\partial A_z/\partial t)+\sigma(\partial \varphi/\partial z)$ is the eddy current density induced by the unsteady electromagnetic field. $\sigma(\partial A_z/\partial t)+\sigma(\partial \varphi/\partial z)$ is not uniform and its integral over the cross-section of the conductor is zero. Hence, in the case of the unsteady current, distribution of current density $J_0-\sigma(\partial A_z/\partial t)-\sigma(\partial \varphi/\partial z)$ is not uniform according to the influence of eddy current caused by electromagnetic induction. Fig. 3 shows the two-dimensional model used to analyze the electromagnetic field. Wire was placed parallel to a flat workpiece. To determine the permeability and conductivity in the analysis area, calculations were carried out using brass wire, steel and copper workpieces, and in air. Considering the computation