Eddy Current Analysis for the Pipe Welding

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***Abstract*— The pipe welder is one of the applications of induction heating. In this paper, the eddy current distribution and the Joule loss on the pipe surface were calculated by a finite element method. A tetrahedral linear edge element and an impedance boundary condition were incorporated to the finite element method for the three-dimensional eddy current analysis. The impedance boundary condition was applied to the pipe surface because the penetration depth was very small. The computation results of eddy current and Joule loss distributions of a pipe welder model are shown.**

***Index Terms*— pipe welding, induction heating, eddy current analysis, finite element method.**

I. INTRODUCTION

With increasing frequency and capacity of the power semiconductor devices, induction heating comes to use generally in the industrial fields. The induction pipe welder is a machine which rolls the plate into a cylinder by squeeze rollers and welds the seam by concentrated induction current to make pipes from plates. The welder is constructed of an inverter, an exciting coil, squeeze rollers and a ferromagnetic bar inserted into the bent plate. The frequency of the inverter is several hundred kilohertz and the power source is several hundred kilowatts. As the technical theme, it is required to obtain the uniform heating at the seam of pipe that can produce a high-quality and consistent tube. In order to design the induction heating pipe welder, it is important to evaluate the eddy current distribution and the Joule loss on the pipe surface.

For the analysis of eddy current distribution and Joule loss, we developed a three-dimensional finite element program using a tetrahedral linear edge element in which two unknowns are set on each edge. Furthermore, a surface impedance boundary condition is applied to the surface of the pipe because of the small penetration depth. Reference [1] summarized the numerus papers on the edge elements and surface impedance condition. In this paper, the formulation of the finite element method adopting the surface impedance boundary condition and the calculated results are described.

II. TUBE WELDING

Fig. 1 shows the structure of a pipe welder using induction heating. The ferromagnetic bar which is called an impeder controls the distribution of magnetic flux to reduce stray current.

A manufacturing process of the tube welding is done by the following sequence.

1) The flat plate is rolled into a cylinder with a small gap between the edges to be jointed by the squeeze rollers.

2) The edges are heated to the welding temperature by induced eddy current, and the weld is formed by the pressure from the squeeze rollers.

3) At the final process, the tube is cooled by water and cut into the required length by shears.

At the heating part, it is necessary to concentrate the eddy current around the welding point and decrease the width of heating area in order to improve the efficiency of the welding.

III. FINITE ELEMENT METHOD

The governing equation of magnetic field with sinusoidal time dependence is given by

$$\nabla \times \boldsymbol{H} = j\omega \boldsymbol{D} + \boldsymbol{J} + \boldsymbol{J}_0 \tag{1}$$

where $\boldsymbol{H}$ is the magnetic field strength, $\boldsymbol{J}$ the eddy current density, $\boldsymbol{J}_0$ the source current density, $\boldsymbol{D}$ the electric flux density, ω the angular frequency.

After applying the Galerkin's weighted residual equation to (1) and substituting $\boldsymbol{D} = \varepsilon^* \boldsymbol{E}$, $\boldsymbol{E} = -j\omega A$, $\boldsymbol{H} = \boldsymbol{B}/\mu$ and $\boldsymbol{B} = \nabla \times \boldsymbol{A}$, we can obtained following equation for the computation model shown in Fig. 2.

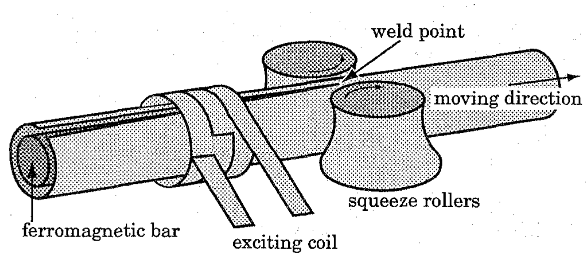

Fig. 1. Pipe weldar.

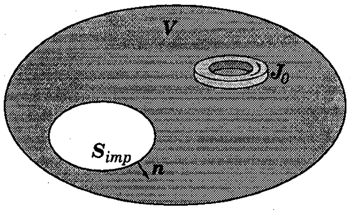

Fig. 2. Computation model.

$$\iiint_V \left(\frac{1}{\mu} \nabla \times \boldsymbol{N}_i \cdot \nabla \times \boldsymbol{A} - \omega^2 \varepsilon^* \boldsymbol{N}_i \cdot \boldsymbol{A} - \boldsymbol{N}_i \cdot \boldsymbol{J}_0 \right) dv$$

$$+ \iint_{S_{imp}} (\boldsymbol{H}_{imp} \times \boldsymbol{N}_i) \cdot \boldsymbol{n} ds = 0 \tag{2}$$

where $\varepsilon*$ is the complex permittivity, S_{imp} the surface to be applied the surface impedance boundary condition, $\boldsymbol{H}_{imp}$ the magnetic field strength on S_{imp}.

When the penetration depth of conducting body becomes small, fine mesh whose element size is comparable to the penetration depth is required for finite element method and the number of unknowns becomes large. In this case, we can adopt the surface impedance approximation to the surface of the conducting body [2].

By using the surface impedance approximation for the conducting surface, the magnetic field strength $\boldsymbol{H}_{imp}$ in (2) is given by

$$\boldsymbol{H}_{imp} = -(1+j)\sqrt{\frac{\sigma\omega}{2\mu}} \boldsymbol{n} \times \boldsymbol{A}_{imp} \tag{3}$$

Substituting (3), we can obtained the expression of the second term of left hand side of (2) as follows:

$$\iint_{S_{imp}} (\boldsymbol{H}_{imp} \times \boldsymbol{N}_i) \cdot \boldsymbol{n} ds = 0$$

$$= -(1+j)\sqrt{\frac{\sigma\omega}{2\mu}} \iint_{S_{imp}} (\boldsymbol{N}_i \cdot \boldsymbol{A}) ds. \tag{4}$$

A tetrahedral linear edge element is used for the developed finite element program. Fig. 3 shows a tetrahedral element. The tangential components of the magnetic vector potential $\boldsymbol{A}$ along edges are chosen as unknown variables preserving tangential continuity. Two unknown variables are set on each edge.

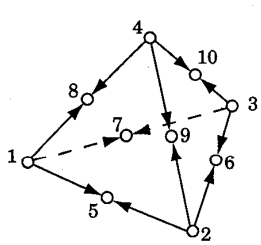

Fig. 3. Tetrahedral linear edge element.

IV. Results of Sphere Model

In order to verify the accuracy of the developed finite element program using the surface impedance boundary condition, we chose a sphere model in a uniform magnetic field. Fig. 4 shows the arrangement of tetrahedra for the sphere model. The surface impedance boundary condition was applied to the surface of the sphere which is shaded in Fig. 4. In the sphere model, the conductivity σ of the sphere is 5×10^7(S/m). Fig. 5 and Fig. 6 show the changes of the total loss of the sphere with respect to frequency of the source field for μ_s=1 and μ_s=1000, respectively. Both results almost agree with theoretical values. The errors for μ_s=1000 depend on the penetration depth. However, the errors for μ_s=1 arise for small penetration depth. Reference [3] shows that error of the surface impedance approximation is caused for small permeability. Therefore, the errors depend on both penetration depth and penetration angle of magnetic flux to the conductor surface.

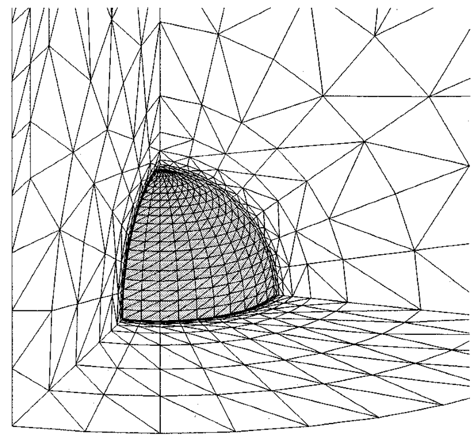

Fig. 4 Arrengememt of tetrahedra for the sphere model.

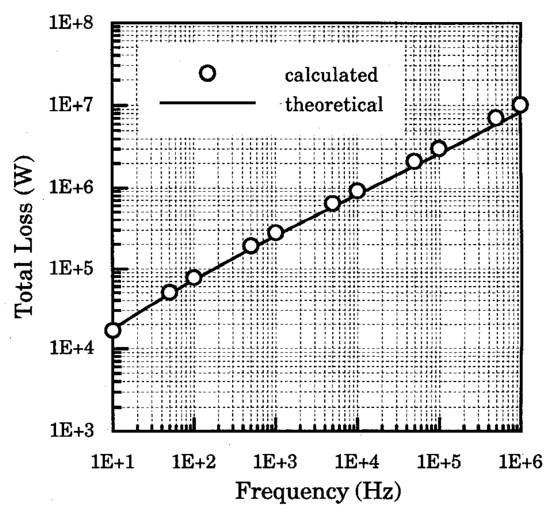

Fig. 5. Total loss of the sphere model: μ_s=1.

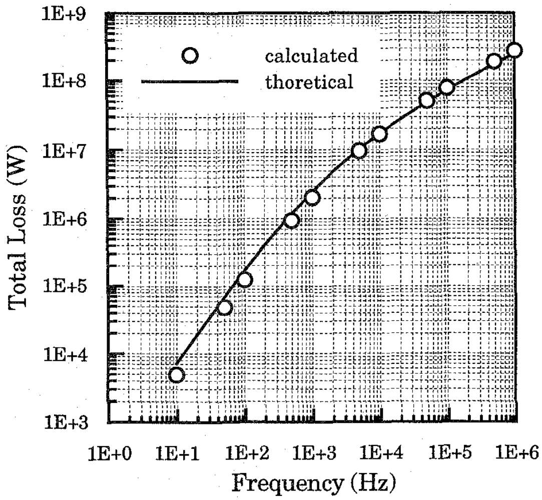

Fig. 6. Total loss of the sphere model: μ_s=1000.

V. RESULTS OF PIPE WELDING MODEL

Fig. 7 shows the calculated results of a pipe welder model. The half region was analyzed because of the symmetry. The numbers of tetrahedra elements and unknowns are 39,788 and 102,016, respectively. Table 1 shows the data for the calculation. The edges are simply jointed each other at the weld point and the crack begins from the weld point. The magnitude of the eddy current vector in Fig. 7(b) was ploted on the logarithm scale. As shown in Fig. 7(c), the Joule loss near weld point can be evaluated.

TABLE 1
DATA OF THE PIPE WELDER MODEL

pipe	ferromagnetic bar	exciting coil
radius = 38.1mm thickness = 1.8mm μ_s = 1000 $\sigma = 1.0\times10^7$ S/m	radius = 26.5mm μ_s = 1800 σ = 0.33 S/m	f = 400kHz I = 1A

VI. CONCLUSION

A finite element program has been developed for the eddy current analysis of the pipe welding. The surface impedance boundary condition is applied to the surface of the conducting pipe in order to reduce the number of unknowns which are required for the modeling of small penetration depth. This approximation brings good agreement between the calculated results and theoretical values of Joule loss for the sphere model. Finally the developed finite element program was applied to a pipe welder model.

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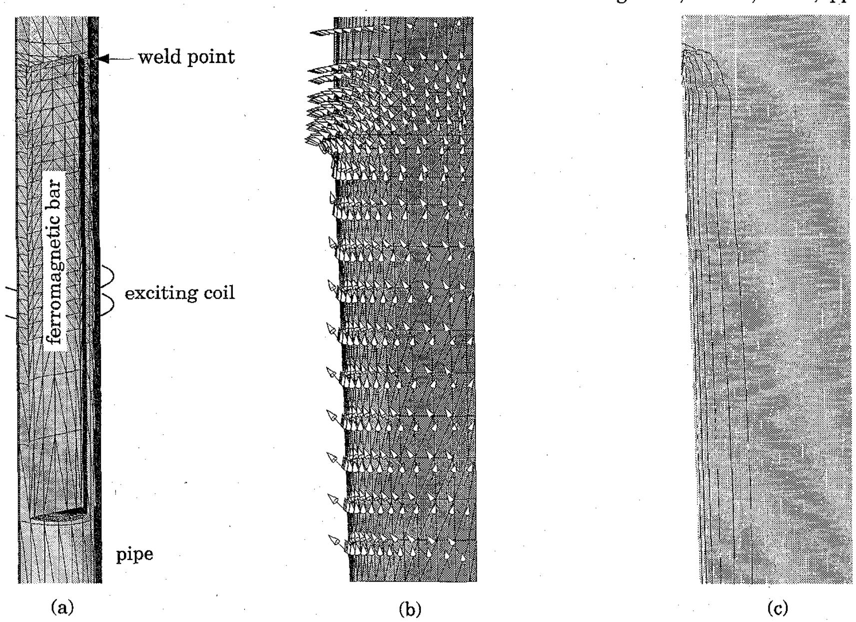

Fig. 7. Calculated results of the pipe welder model,
(a) arrangment of tetrahedra, (b) eddy current distribution near the weld point, (c) Joule loss distribution.