Analysis of induction heating apparatus controlled by two excitation coils with different frequencies

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This paper describes analysis of an induction heating (IH) apparatus for hardening iron rods. The examined IH apparatus is equipped with two excitation coils to control heating characteristic of target materials by changing frequencies of applied voltages. As a fundamental investigation, beat phenomenon due to excitations at different frequencies, which cause instability of control process, are examined by analyzing magnetic fields and eddy currents under various exciting conditions by means of the finite element method. The beat phenomenon of coil currents and flux densities in a target material to be heated are discussed.

1. Introduction

The induction heating (IH) apparatus is useful to harden target materials such as iron, of which the heat source is eddy current loss inside materials caused by alternating magnetic fields. It is widely used in industrial fields, at home, and etc since it has a lot of merits as follows:

(a) It is a clean energy source since it doesn't use flue gases.
(b) It is easy to make the automation and the remote control of the line because of the excellence of the ability of operation and control.
(c) The heating efficiency is high.
(d) Only a necessary part can be partially heated.

Thus, the range of the application field will be expected to be wider in the future. Its application frequency could be from a commercial frequency to several hundreds KHz. In order to control the heating characteristic, it is required to adjust voltages or frequencies applied to excitation coils. However, such an adjustment increases instability of IH system due to the fact that beat phenomenon causes.

This paper described the beat phenomenon of currents in coils, flux densities, and eddy current loss inside materials caused by excitation with different frequencies.

2. Model and conditions for analysis

In this paper, the power source with different voltage and frequencies are applied to excitation coils, and target materials such as iron rods to be heated pass through their excitation coils as shown in Fig. 1. As the shapes of coils and target materials are cylindrical, the axisymmetric finite element method [1] can be applicable to analyze magnetic fields and eddy currents.

When I_{max} and I_{min} are extracted as shown in Fig. 2 of the waveform of the current of the coil, the definition of modulation factor of currents m is Eq. (1).

$$m = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} \qquad (1)$$

It is assumed that the target material is heated at 1200 °C, which is over the Curie point. Consequently, the relative permeability of target material is $\mu_s = 1$. The resistance is set at $\rho = 1.2 \mu\Omega m$. The basic conditions of the coils are shown in Table 1. It analyzed various examinations under these conditions.

2.1 Changing the coil length

It analyzed when changing the length of the coils in the range of $L = 400 \sim 2200$ mm under the condition of the radius of the coils $D = 75$ mm, the radius of target

material to be heated S = 40 mm, the gap between the coils G = 0 mm, 20 mm as well as conditioning $L_1 = L_2$ in analytical model Fig.3. The number of turn and resistance are constant in the value of Table 1.

2.2 Changing the radius of the coils

It analyzed when changing the radius of the coils in the range of D = 35 ～ 75 mm under the condition of the coil length $L_1 = L_2$ = 400mm and the gap between the coils G = 0 mm. Furthermore, It also changed the radius of the target material to be heated S with making the ratio D/S the same under every condition.

2.3 Making the relative relation of the coil length, the radius of the coils, and the radius of the target material constant.

It analyzed when changing the coil length L_1, L_2, the radius of the coils D, and the radius of the target material to be heated S. It used Fig. 3 as a model, and the conditions of the factors being changed are shown in Table 2. As they are shown in Table 2, the relative relations of the coil length, the radius of the coils, and the radius of the target material $L_1/D = L_2/D$ and D/S are equivalent respectively in condition 1, 2, and 3. The Gap between the coils G is 0 mm. The relation of the size of each value is examined whether to influence the modulation factor of the current of the coils.

2.4 Examination of the flux density of target material

It examined the flux densities at points A(z = 0mm), B(z = -80mm), and C(z = -240mm) on the surface of target material, as well as at points D(z = 0mm), E(z = -80mm), and F(z = -240mm) on the line 30 mm away from the center axis under condition 1.
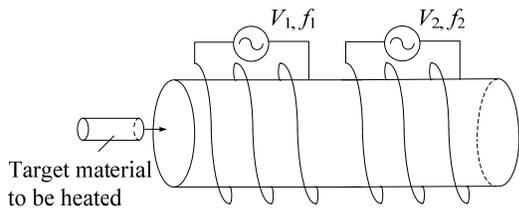

Fig.1 Model of induction heating system controlled by two excitation coils with different frequencies and voltages.
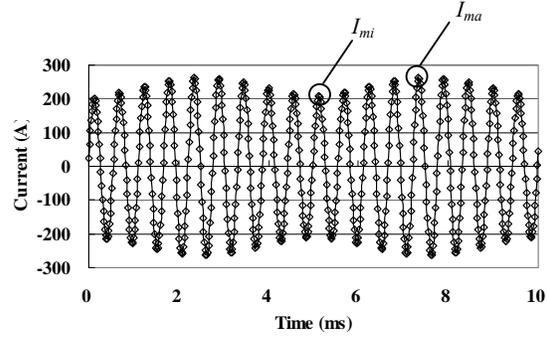

Table 1. Exciting condition of the coils.

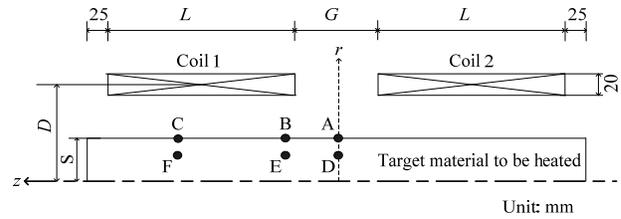|	Coil 1	Coil 2
Frequency(Hz)	2000	1800
Input Voltage(V)	2400	1809
Turn	140	170
Resistance of coil(Ω)	0.059	0.089

Fig. 3. Analyzed model.

Table 2 Condition of the coils and the target material when changing the length as well as the radius of the coils, and the radius of the target material.

	Condition 1	Condition 2	Condition 3
L_1 (mm)	400.0	520.0	640.0
L_2 (mm)	400.0	520.0	640.0
D (mm)	75.0	97.5	120.0
S (mm)	40.0	52.0	64.0
$L_1/D = L_2/D$	5.3	5.3	5.3
D/S	1.9	1.9	1.9

2.5 Examination of the examination of eddy current loss inside target material

It examined the eddy current loss at points A(z = 0mm), B(z = -80mm), C(z = -240mm) on the surface of target material, as well as at points D(z = 0mm), E(z = -80mm), and F(z = -240mm) on the line 30 mm away from the center axis under condition 1.

3. Results of analysis

It shows the results of the analyses and examination under various conditions.

3.1 Changing the coil length

Fig. 4 shows the modulation factors of the currents when changing the length of the coils in the range of $L =$ 400 ~ 2200 mm. The beat phenomenon was observed, of which the frequency is 200 Hz and is equal to the difference between the frequencies of the two currents at excitation coils. They increase when the length of coils becomes shorter. A big beat phenomenon is caused in the waveform of the flux density in the vicinity of J, air part, in Fig.5, and the beat phenomenon is hardly caused in the vicinity of K, which is far from the other coil. Moreover, the longer the coil length is, the smaller the beat phenomenon of the waveform of flux density is in the vicinity of K. Furthermore, the larger generation voltage is caused by the flux of the other coil when the coil is short because the number of coil windings and the input voltage are the same even if the length of the coils is changed in the analysis; therefore, the modulation factors increase.

It is thought that the modulation factor of current in the coil 2 is larger than that in the coil 1 because the amplitude of current in the coil 2 is smaller as well as the magnetic field produced by the coil 1 is bigger than that of the coil 2.

3.2 Changing the radius of the coils

Fig. 6 shows the modulation factors of the currents when changing the radius of the coils in the range of $D =$ 35 ~ 75 mm. They decrease as the radius of the coils becomes smaller.

Because the basic condition such as the voltage of the coils is constant as well as the sectional area of the coils becomes small by reducing the radius, a basic element of the current grows by the reactance element becomes small. Though, it also leads to the increase in the width of beat phenomenon due to the fact that the reactance element becomes small, the magnetic field which is produced by the other coil becomes smaller by decreasing the radius of the coils. Therefore, the changing in the amplitude of the current is bigger than that of the beat phenomenon.

Thus, it is thought that the size of the modulation factor of currents becomes small as the radius is reduced.
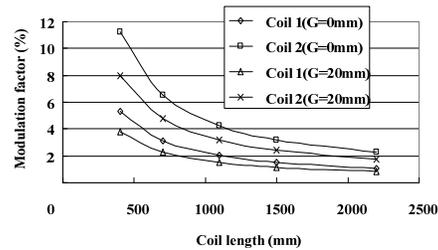

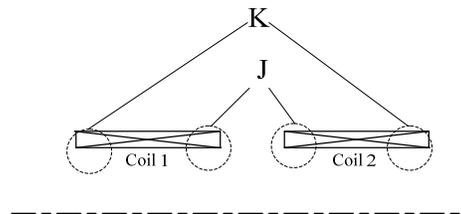*Fig. 4. Modulation factor of coil currents.*

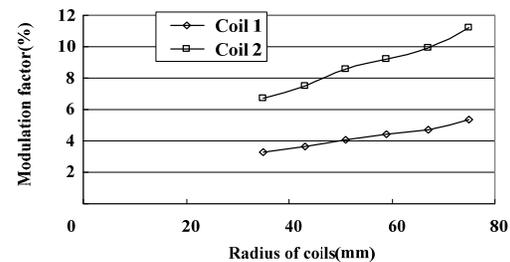*Fig.5 Evaluation points of examination of the coil length.*

Fig. 6. Modulation factor of coil currents.

3.3 Making the relative relation of the coil length, the radius of the coils, and the radius of the target material constant

Table 3 shows the modulation factors of the currents when changing the length and the radius of the coils as well as the radius of the target material. Almost the same modulation factors in the currents are caused in condition 1, 2, and 3. Therefore, it is thought that a relative relation among the radius of the coils D, length of the coils L, and the radius of target material S are greatly related to the beat phenomenon under the condition that the basic condition such as the voltage and the number of volumes are constant.

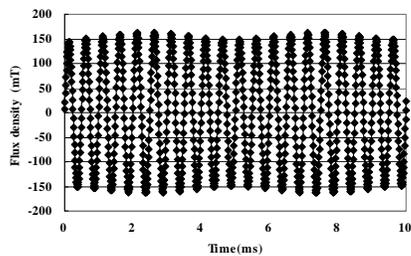*Table 3 Modulation factor of the currents in condition 1, 2, and 3.*

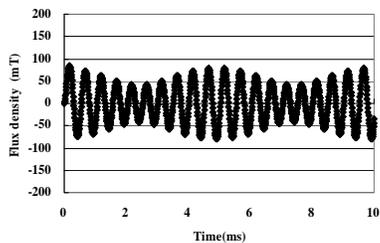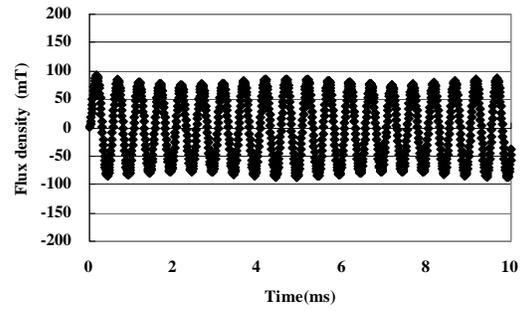|	I_1	I_2
Condition 1	5.3%	11.2%
Condition 2	5.2%	11.0%
Condition 3	5.2%	10.9%
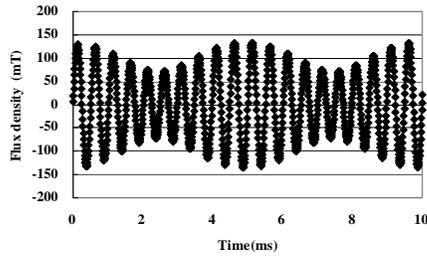
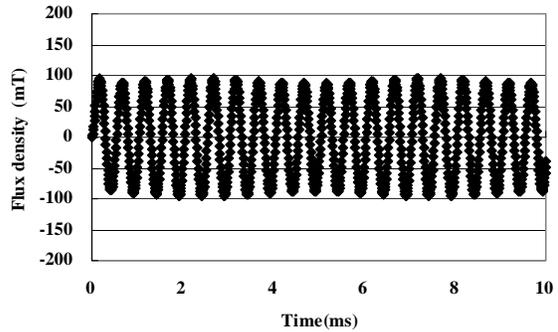

(a) point A
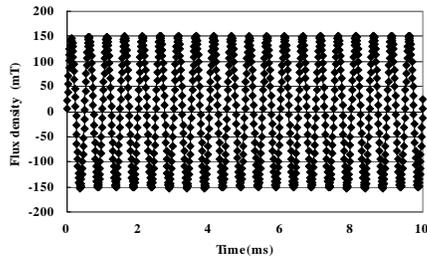
(b) point B
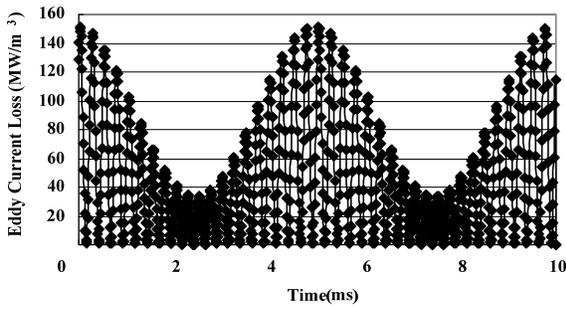

(c) point C

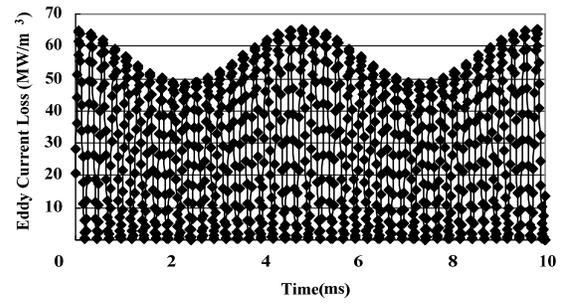(d) point D

(e) point E

(f) point F

Fig.7. Flux density waveforms at points A ～ F.

### 3.4 Result of the examination of the flux density inside target material.

Fig. 7 shows the waveforms of flux densities at points from A to F. The beat phenomenon was observed, of which the frequency is 200 Hz and is equal to the difference between the frequencies of the two excitation coils. The beat is dependent on the position. At the points A and D, the large beat was observed as shown in Figs. 7 (a) and (d). The phases of beats at the points A, D, and C, F were opposite as shown in Figs. 7 (a) and (c). This means that the influence of the counter magnetic field generated from the coil 1 was stronger than the magnetic field generated from the coil 2 at the point C, although the influence of the magnetic field generated from the coil 2 is considerably large at the point A. The amplitude of beat at the point B was fairly small. This means that the amplitudes of magnetic fields generated from the counter magnetic field of coil 1 and the coil 2 were similar to each other at the point B.
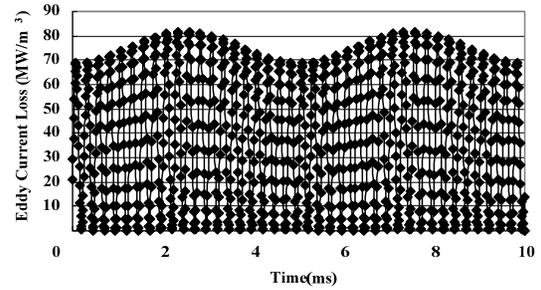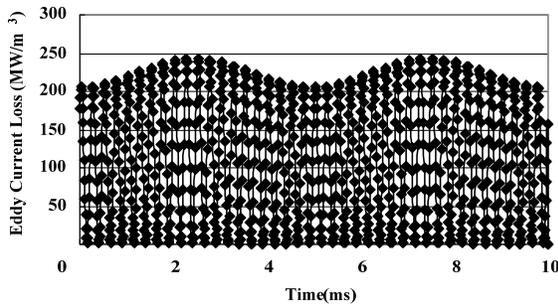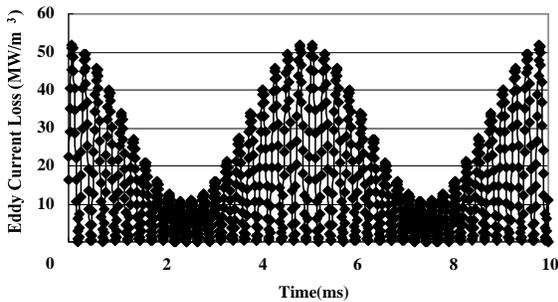
(a) point A

(b) point B

(c) point C

(d) point D

(e) point E
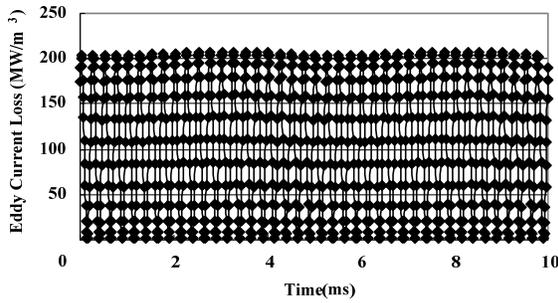
(f) point F

Fig. 8. Eddy current loss waveforms at points A ～ F.

3.5 Examination of eddy current loss inside target material

Fig. 8 shows the waveform of eddy current loss at points from A to F. Also, Fig. 9 (a) shows the average eddy current loss of one cycle on the surface of target material in the range of Z = -100 ～ 100mm under the condition as follows:

(1) Table 1

(2) Input only coil 1 with the amplitude and frequency of applied voltage: V_1 = 2.4 kV and f_1 = 2 kHz

(3) Input only coil 2, with the amplitude and frequency of applied voltage: V_2 = 1.8 kV and f_2 = 1.8 kHz

(4) Result of addition of the eddy current loss of (2) and (3)

Moreover, Fig. 9 (b) shows the same kind of the figure which is on the line 30mm away from the center of the target material.

The beat phenomenon was observed, of which the frequency is 200 Hz. Furthermore, it is clarified that the beat phenomenon of eddy current loss of each point is similar to that of the flux density, and it is understood

that the amplitude of modulation factor of eddy current loss is greatly related to that of flux density. However, if it is assumed that target material moves thorough apparatus in low speed, it is thought that a similar loss occurs in target material when target material passes the same place since the change of the conduction of heat is not extreme like the change in the magnetic field, and it is generally thought that the amount that multiplies a certain loss of the fixed time to be generation of the heat when analyzing the heat conduction. Therefore, it is thought that the beat phenomenon is not a major issue upon heating target material directly, though it is thought the beat phenomenon causes a big influence to the power supply control. However, Fig. 9 shows that the loss has lowered especially in the vicinity of $z = 0$ mm compared with the case which input the voltage by one. It occurs due to the fact that the beat phenomenon is caused in the waveform of eddy current loss.

Accordingly, the apparatus should be designed with considering the influence of the beat phenomenon on the power supply control and a decrease in the loss inside target materials

4. Conclusions

It is clarified that the length and the radius of the excitation coils greatly affect the beat phenomenon. Moreover, the amplitude and the phase of beaten flux density as well as eddy current loss inside target material to be heated are dependent on the position.

The influence of the beat phenomenon when heating will be examined by doing heat conduction analysis in the future.
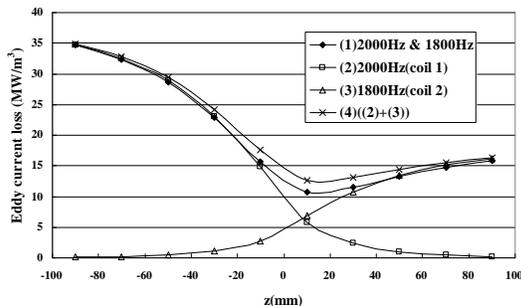
References

[1] T. Nakata, N. Takahashi, Morikita, pp. 7-19, 1986 (in Japanese).

[2] K. Honda, T. Sakurai, J. Chun-Feng, Y. Ishihara, T. Todaka, Proceedings of MAGDA Conference in Kiriu, pp. 336-339, 2006 (in Japanese).

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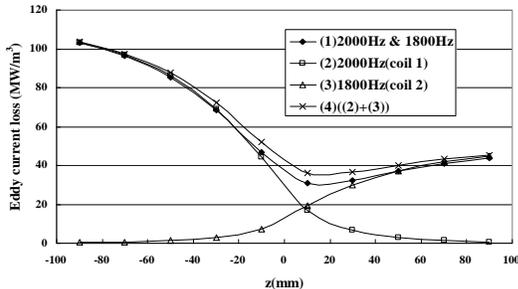
(a) r = 40mm

(b) r = 30mm

Fig. 9. Average eddy current loss of each point.