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Experimental Investigation of the Electromagnetic Force Acting on the Metallic Materials in Pulse High Magnetic Fields

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In the pulsed high magnetic field, electromagnetic force is acted on the metallic materials with high electrical conductivity. Using this principle, the evaluation system of strength for materials in the high magnetic fields was developed and tested. Cu and Al-6063 pipes are used in this study. Water-cooled bitter-type pulse magnet is used. Time constant of pulse field is 2.6 ms. The pipes are crushed above 10 T, which indicates huge electromagnetic force is acted. From the experimental results, we estimated the electromagnetic force. Obtained centrifugal stress directed to the central axis is quantitatively the same as yield point.

Key Words : Electromagnetic Force, Metallic Pipe, High Magnetic Field, Copper, Aluminum.

1. INTRODUCTION

Nowadays, many engineering instruments are used in high magnetic fields. Most familiar instrument in our daily life is an electromagnetic motor. JR Tokai Railway Co. Ltd. is running experiments of the Linear Motor Cars [1]. Aichi prefecture is also planning a Linear Motor Cars system [2]. Many electrical magnets are lined up on the passage, and the cars are floating and moving by the repulsive and attractive magnetic forces. Recently, superconducting magnets are used for the magnet. Superconducting magnet has lower the electrical power loss compared to the normal conducting magnet. The magnetic field from the magnet coil is few Tesla, which is about 10 times larger than the usual permanent magnet. Other example is an electrical power generation system used in Nuclear-Fusion [3]. High magnetic field is needed for starting up the plasma in the reactor. In order to use for the test of metallic materials, sufficient strength is required in these high magnetic field systems. Huge magnetic force is acting on the magnetic material by the magnetic field. Therefore we must avoid using magnetic materials in the high magnetic field. On the other hand, magnetic force is also acting on the non-magnetic materials. When the magnetic field is changing (for example, AC magnetic field), eddy current is loaded on the metallic materials. Due to the electrical current, large Faraday force is acting on the material [4]. For the materials are weak compared with the magnetic force, they are either deformed or broken. In this reason, an evaluation test system for magnetic force is needed. We made the evaluation test system of metallic materials using a pulsed high-field magnet up to 20 T. This system is a conventional magnet for generating pulsed (AC) high magnetic fields. Using a large capacitor (total 8 mF) and a magnet coil, short pulse field can be generated. In this paper, experimental apparatus and experimental results on Copper and Aluminum pipes are presented.

2. EXPERIMENTAL SETUP

2.1 Pulse magnet system

Fig. 1 shows the schematic drawing of pulse magnet system [5]. In the Figure, C is the capacitor of the generator. SW means the switch, which is using an Ignatron. Water-cooled pulse magnet is used in this system. The inductance L is 8.4×10^{-5} H. AC 200V is transferred to higher voltage (maximum 5 kV) by the inductor and the capacitor C is charged via the load resistor R. In this system, the capacitance C is 8.0 mF. The maximum energy, which can be stored in the capacitor bank, is 100 kJ. When the capacitor is being charged until the target voltage, switch SW remains turned on. Then the electric current, about 10 kA at 14 T, flows in the pulse magnet. Time dependence of the magnetic field in the pulse magnet is illustrated in Fig. 2. The duration time of the magnetic field is 2.6 msec, which is exactly the as same as the

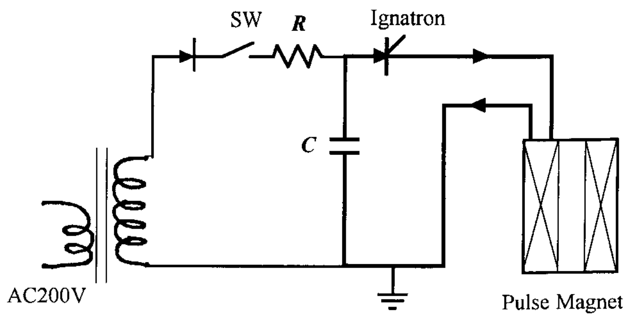

Figure 1 A schematic drawing of pulse magnet system.

result of calculation,

$$\tau=\pi\sqrt{LC}=\pi\times\sqrt{(8.4\times10^{-5})\times8.0\times10^{-3}}=2.6\times10^{-3}[\mathrm{s}] \quad (1),$$

where, τ is the duration time of the pulse field. The frequency f of pulse field is,

$$f=\frac{1}{2\pi\sqrt{LC}}=\frac{1}{2\tau}=\frac{1}{2\times2.6\times10^{-3}}=192\ [\mathrm{Hz}] \quad (2).$$

The electric resistance of the circuit is very small compared to the reactance due to the induction L and capacitance C. Therefore we can ignore the effect of the resistance.

2.2 Magnetoelectric Induction [6]

When the magnetic field is induced to the pulse magnet, two inductions are to be considered in this experimental system. One is the self inductance, which occurs in the coil itself. The other is the mutual induction between the pulse magnet and the metallic sample.

When the electric current in the magnet coil changes, self induction occurs due to the change of the magnetic field, which is generated by the current itself. The magnetic flux Φ is proportional to the current I. Therefore,

$$\Phi=LI \quad (3)$$

where the proportional constant L is the self inductance of the magnet coil. The induction voltage of the magnet V_r is proportional to the change of the magnetic flux $d\Phi/dt$. Therefore,

$$V_r=-\frac{d\Phi}{dt}=-L\frac{dI}{dt} \quad (4)$$

In this experiment, the metallic pipe sample is also a single turn coil located in the magnet coil. Accordingly, the self inductance L and induction voltage V_r can be described using equations (3) and (4).

2.3 Magnetic force acting in the metallic pipe

When the magnetic field is induced, the electromagnetic force is acted on the metallic pipe. Fig. 3 shows the schematic drawing of the electromagnetic force acting on the metallic pipe. The central axis of the pipe is parallel to the magnetic field, B. I is the electric current flowing in the sample and F is the electromagnetic force. In the pulse field, B changes with time. Then the magnetoelectric induction acts in the pipe and the circular electric current I flows in the pipe. Consequently, electromagnetic force F acts according to Faraday's law,

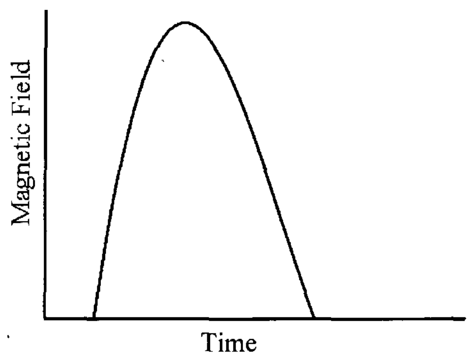

Figure 2 Time dependence of the magnetic field in the pulse magnet.

$$F=IBl \quad (5)$$

where l is the circumference of the pipe. The direction of the force F is directed toward the center axis of the pipe.

The current I is give by Ohm's law,

$$I=V_r/R \quad (6)$$

where V_r is the induction voltage and R is the electrical resistance of the pipe.

From Eq.(5) and (6), the electromagnetic force F is obtained as,

$$F=\frac{V_r}{R}Bl \quad (7).$$

The electrical resistance R is,

$$R=\rho\frac{l}{S_1}=\rho\frac{l}{l_0d} \quad (8)$$

where ρ is the resistivity, d is the thickness of the pipe, S_1 is the longitudinal cross sectional area of the pipe, and l_0 is the length of the pipe. Substituting Eq.(4) and (8) in Eq.(7), electromagnetic force F directed toward the center axis of the pipe is,

$$F=-\frac{\frac{d\Phi}{dt}}{\frac{l}{\rho l_0 d}}B \quad (9).$$

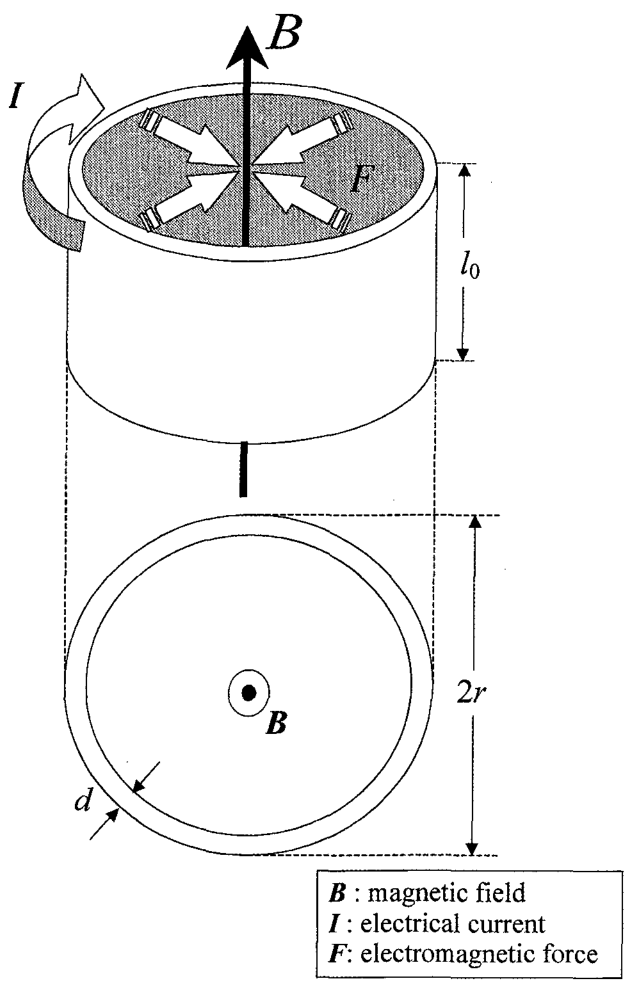

Figure 3 A schematic drawing of the magnetic force acting in the metallic pipe.

The magnetic flux Φ passing through the pipe is presented using the circular cross section of the pipe S_2 as,

$$\Phi = BS_2 \qquad (10).$$

Substituting Eq.(10) in Eq.(9),

$$F = -\frac{S_2 \frac{dB}{dt}}{\frac{l}{\rho\, l_0 d}} Bl = -\pi r^2 \frac{1}{\rho} l_0 B d \frac{dB}{dt} \qquad (11).$$

where r is a radius of the pipe.

Using Eq.(11), the electromagnetic force F is calculated.
A centrifugal stress σ directed to the central axis is expressed as,

$$\sigma = F/(2\pi r l_0) \qquad (12)$$

where $2\pi r l_0$ is outer surface area of the sample pipe.

2.4 Water cooled Bitter-type magnet

Usually, pulse magnet is a solenoid-type magnet and it is cooled down in the liquid nitrogen bath 77 K. It is to reduce the electrical resistance of the magnet. When we investigate the magnetic properties and strength of the industrial materials in high magnetic field, experiment must be done at room temperature. Then we must make a cryostat in order to carry out the experiment at room temperature. In this case, the sample space is restricted to 10 mm diameter at most. In this study, we prepared the water-cooled pulse magnet, shown in Fig. 4. This magnet works at room temperature. Therefore the cryostat is not required. The coil of this magnet is made of bitter plates, shown in Fig. 5. These are thin circular plates made by Cu-Ag alloy with a thickness of 1.0 mm. Holes allow flow of water for cooling. Glass fiber sheets are laid between bitter plates for electrical insulation. When the magnet is connected to the capacitor bank, current flows spirally and the magnetic field is generated in the magnet. Compared to the solenoid magnet, it is easier to cool down and electrical resistance is much smaller. Inner diameter of the magnet is 26 mm. In this magnet system, cryostat is not needed ; therefore we can use inner

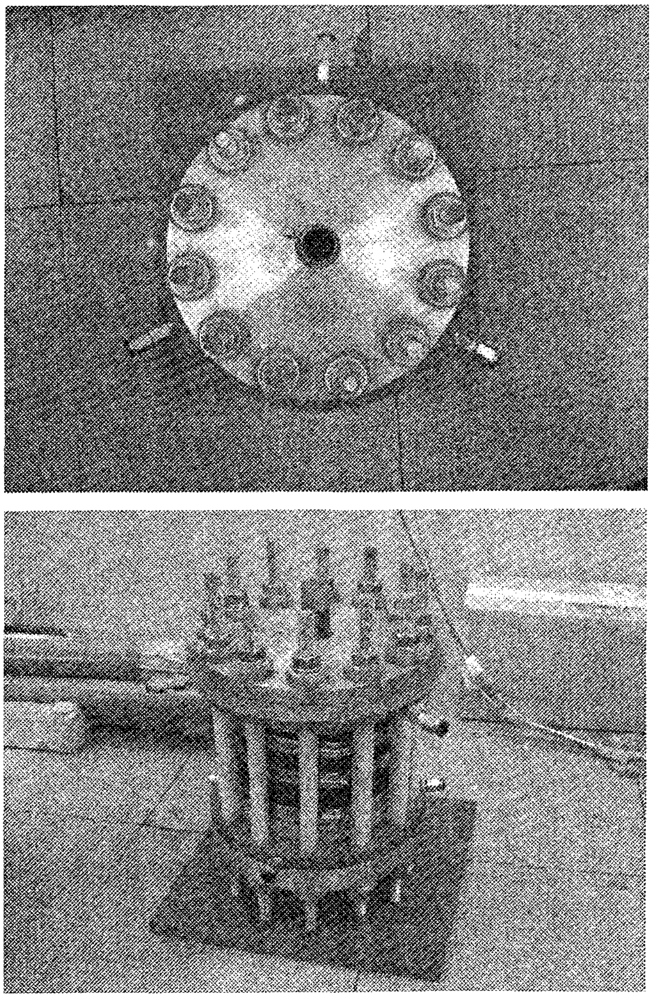

Figure 4 Picture of the water-cooled pulse magnet.

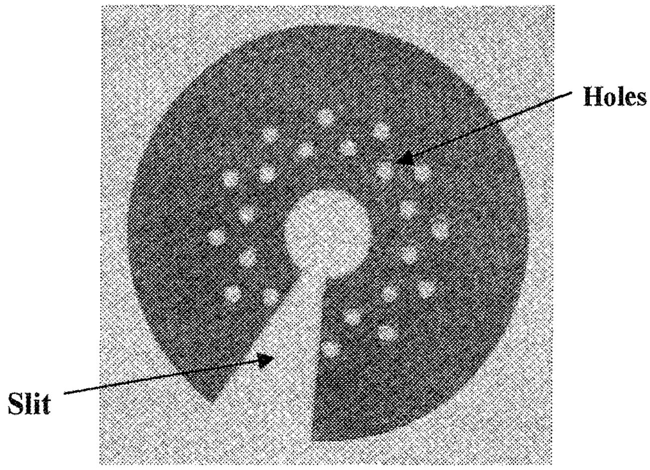

Figure 5 Picture of the bitter plate.

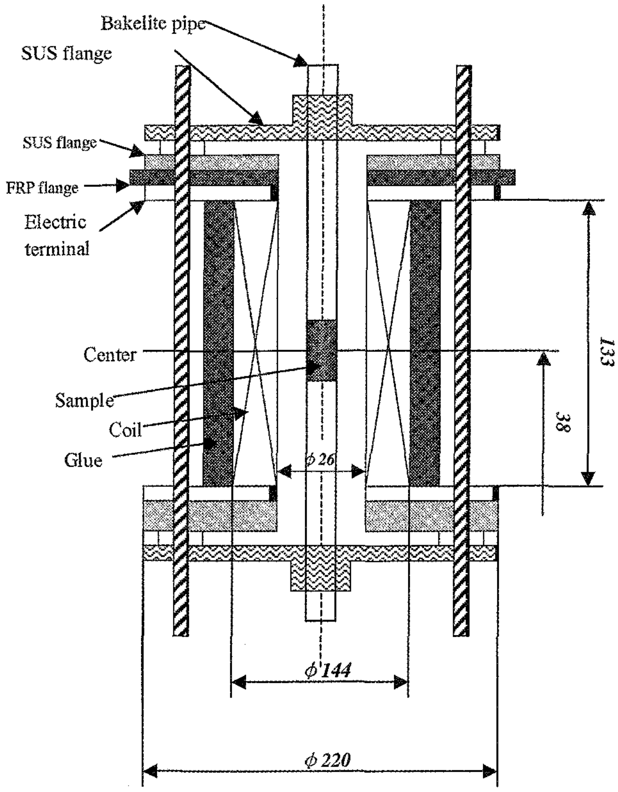

Figure 6 A schematic drawing of the magnet.

space of the magnet for sample mount.

A schematic drawing of the magnet is illustrated in Fig. 6. 100 Bitter plates are piled up and fixed by long stainless bolts. The electrode plates are made by brass, and waterspouts are installed in these plates. The sample is placed at the center of the magnet covered with a pipe-shaped transparent polymer sheet. The sample is loosely fixed by Scotch tape in order to keep floating freely in the air.

Magnetic field is measured by a pick-up coil, which is wired on the glass pipe. In the pulsed magnetic field, induction voltage is generated in the pick-up coil. We measured the induction voltage and calculated the magnetic field.

3. RESULTS AND DISCUSSIONS

In this experiment, we used two kinds of samples. One is pure copper (Cu) and the other is aluminum alloy, Al-6063. The elements of Cu sample are 0.04-0.15% Phosphorus (P) and 99.9% Cu (mass %). On the other hand, Al-6063 alloy contains 0.2-0.6% Si, 0.1% Cu, 0.35% Fe, 0.1% Mn, 0.45-0.9% Mg, 0.1% Zn, 0.1% Ti and 0.1% Cr [7]. As for magnetic properties, Cu is a diamagnet (magnetic susceptibility $\chi_M = -5.46 \times 10^{-6}$ emu/mole at 293 K) and Al is a paramagnet ($\chi_M = +16.4 \times 10^{-6}$ emu/mole at 293 K) [8]. Consequently, the increase of the magnetic field is 10^{-5}-10^{-6} times smaller than that of ferromagnets. The quantity of the magnetic elements, Fe , Cr *et al* in Al-6063 alloy is ignorable. Therefore, in this study, Al-6063 alloy is considered as a paramagnetic material.

Table 1 Specifications of the metallic samples.

sample	outer diameter $2r$ [mm]	thickness d [mm]	length l_0 [mm]
Cu	19.0	1.00	25.0
Al-6063	19.0	1.00	25.0

The typical specifications of the samples are listed on Table 1. For both samples, outer diameter is 19.0 mm and the thickness is 1.0 mm. The electrical resistivity of Cu at room temperature is smaller than that of Al alloy. The length of each sample is 25 mm. Cu pipe was crushed at 12.0 T. On the other hand, Al alloy pipe was crushed at 15.3 T. The pictures of the crashed pipes are presented in Fig. 7. Linear crack was made in Al-6063 pipe and melted due to Joule heating by large electrical current. The magnetic field which is crashed did not change when the sample length l_0 was changed to 50 mm. With regards to this experimental study, differences between Cu and Al pipes are

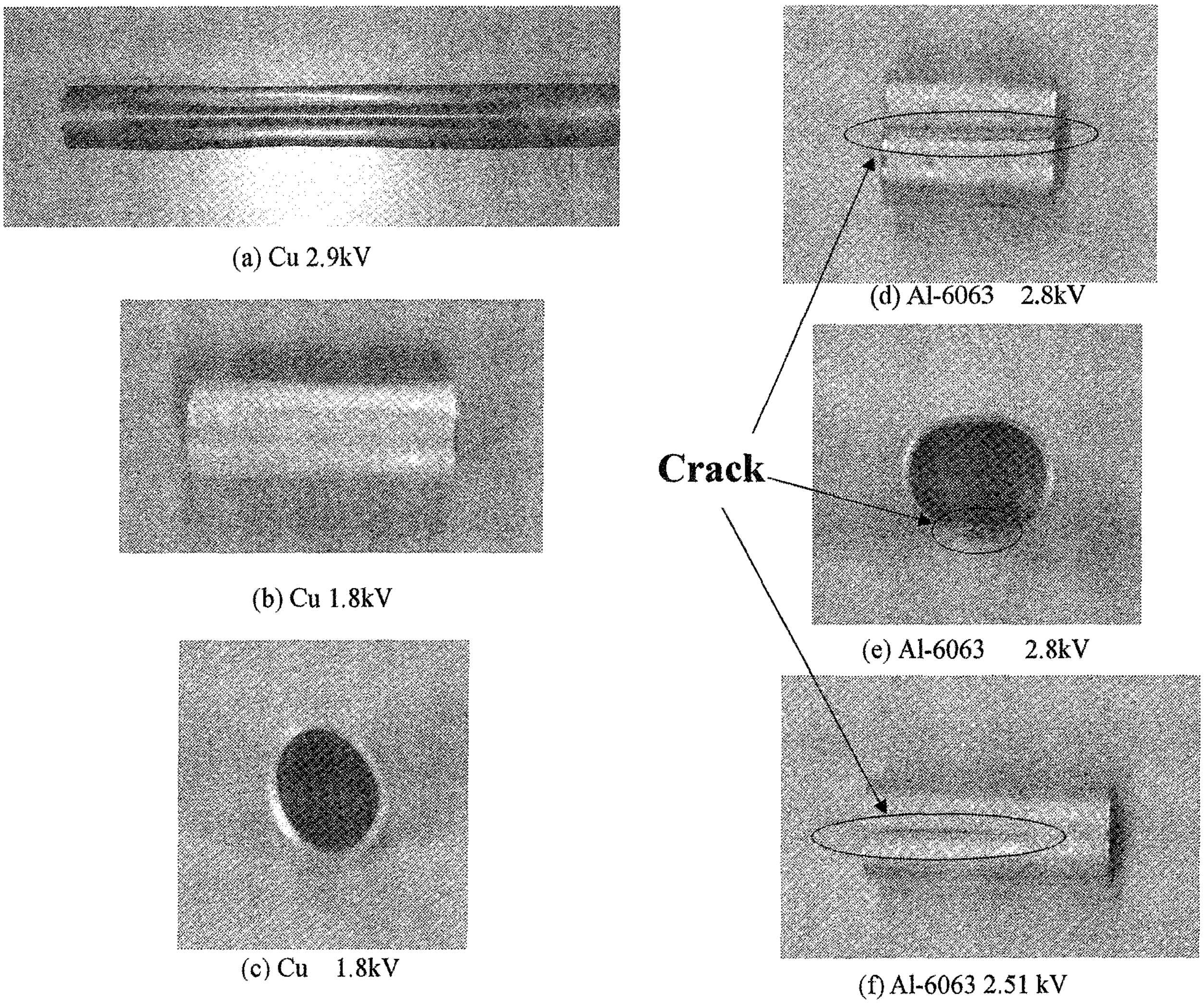

Figure 7 Photos of the crashed pipes.

Table 2 Estimated values of the centrifugal stress σ directed toward the central axis due to electromagnetic force acting on the sample during the sample crush. V_C : charged voltage, B_{max} : maximum field, ρ : electrical resistivity. The yield point [9] and Young's modulus E are also listed. The electrical resistivity and Young's modulus data are prepaired by Hakudo Co. Ltd.[8].

sample	V_C [kV]	B_{max} [T]	ρ [$10^{-8}\Omega$m]	$(B(dB/dt))_{max}$ [10^5T^2/s]	obtained σ (this study) [MPa]	yield point [MPa]	E [MPa]
Cu	1.80	12.0	1.897	1.05	26.3±2.6	30	11000
Al-6063	2.30	15.3	6.323	2.44	18.3±1.8	15	7000

electrical resistivity and hardness. When we apply same magnetic field, the currents induced in the samples are not the same because of the difference in the electrical resistivity. Therefore, under the same circumstance, stronger magnetic force is applied on the Cu pipe. It is also assumed that the hardness determines the minimum magnetic force to crush the pipes. Using Eq.(11) and (12), a centrifugal stress σ directed to the central axis due to the magnetic force when the sample is crushed, is estimated. Fig. 8 shows the magnetic field B, the change of magnetic field dB/dt, and $(B(dB/dt))$ for Cu pipe. The Cu pipe is crushed at the charge voltage $V_c = 1.80$ kV, which corresponds to 12.0 T of maximum field. The maximum value of $(B(dB/dt))$ is 1.05×10^5 [T^2/s] and a centrifugal stress σ directed to the central axis is 26.3 MPa. On the other hand, a yield point of Cu is 30 MPa [9], which is the same value as σ. The electromagnetic force acted on Al-6063 pipe

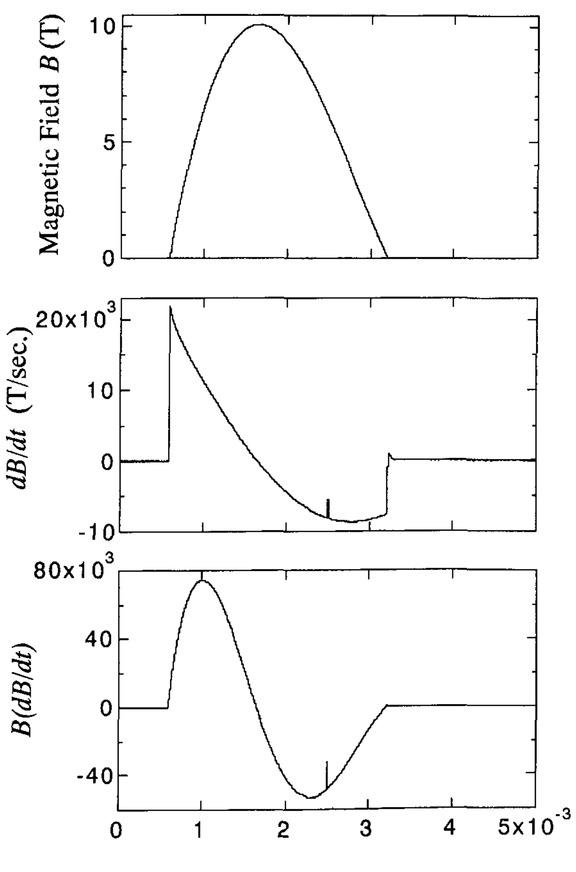

Figure 8 Time evolution of the magnetic field B, derivative dB/dt, and $(B(dB/dt))$ for Cu pipe.

is also calculated in the same way. In Table 2, a centrifugal stress σ of the magnetic force acting on each sample is listed. It also lists the electrical resistivity ρ and yield point. T is the temperature of the sample in the magnetic field measured by a digital thermometer (SHIMAZU PD-600A). For $0 < T < 100$℃, the electrical resistivity ρ of the metallic material is presented in terms of T as,

$$\rho = \rho_0(1 + \alpha T) \tag{13}$$

where ρ_0 is a resistivity at $T = 0$℃ and α is a temperature coefficient [8]. The resistivity ρ of Cu is obtained using Eq.(13). The electrical conductivities of these two samples are 100% IACS for Cu and 30% IACS for Al-6063 [7]. Then the electrical resistivity of Al-6063 is calculated, which is show in Table 2.

The centrifugal stress σ, which is obtained in this experimental study listed in Table 2. The error in this experiment is estimated about 10%. σ is almost the same as the yield point. The centrifugal stress of Al-6063pipe is smaller than that of Cu pipe. This is consistent with the yield point. It is notable that the ratio of σ between Cu and Al-6063 is almost the same as that of Young's modulus. Therefore this evaluation system of strength for materials, which are employed in the high magnetic fields, is quite useful for testing metallic materials. Further experimental study using other metallic materials and other shapes (cubic, rectangle or spherical) is needed in order to search for new materials using in magnetic field.

4. CONCLUSION

The evaluation system of strength for materials under high magnetic fields has been constructed. Cu and Al-6063 pipes are tested in this study. Water-cooled bitter-type pulse magnet is used. The pipes are crushed above 10 T, which indicates huge centrifugal stress σ is directed toward the central axis due to electromagnetic force. From the experimental results, we estimated centrifugal stress σ, which is consistent with yield point and Young's modulus, which means this experimental system is useful for mechanical tests of metallic materials in high magnetic field.

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