

## Electromagnetic Tube Bulging by the Direct Electrode Contact Method and the Solenoidal Coil Method

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Aluminum tube workpieces are bulged electromagnetically by the two methods. The experiments carried out clarify the characteristics of the direct electrode contact method, where the discharge current of 810 kA maximum from a 800- $\mu$ F and 5-kJ capacitor bank flows directly through a workpiece.

### 1. Introduction

Two current-carrying conductors placed adjacent to each other are acted on by the electromagnetic force which may be enough to deform one or both of them. This force can be used for forming metal tubes. In the conventional method of electromagnetic tube bulging, one of the two conductors is a solenoidal coil inserted in the other as workpiece. The rapidly changing magnetic field associated with the discharge current from a capacitor bank through the solenoidal coil induces eddy currents in the workpiece, the magnitude of which determines the electromagnetic forming force. The conventional method with such a solenoidal coil is used in industry [1, 2] and described in many papers [3-6], so its features are almost well-known. This method, however, has such weak-points as unfitness for materials with a resistivity above 5  $\mu\Omega \cdot \text{cm}$  [1] and a short life of the coil.

In the other electromagnetic method of tube bulging, called the direct electrode contact method [7], a simple rod as current-carrying conductor is placed inside a metal tube workpiece so that discharge current will flow directly through the workpiece in close contact with electrodes. This method has such

advantages as no use for a forming coil with a short life and less effects of the electric resistivity of the workpiece than the conventional method, which fact enables to form workpieces of steel, including stainless steel, for which the conventional method is unfit. However, this method involving such technological problems as avoiding possible erosions on contacting surfaces with the electrodes, which are caused by an extremely large current, and decreasing the impedance of the discharge circuit in accordance with the very low impedance of the electrode-and-workpiece section, experiments by the direct electrode contact method have been reported only by us [8,9].

In this paper we describe the results of our experiments of metal tube bulging by the direct electrode contact method, comparing with those obtained by the solenoidal coil method to clarify the features of the former.

### 2. Bulging by the Direct Electrode Contact Method

#### 2.1 Experimental apparatus

The electromagnetic forming apparatus (Fig.1) comprises a capacitor discharge circuit with a low impedance. Fig.2 shows the circuit

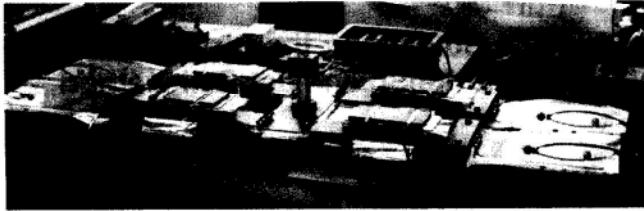


Fig.1  
Photograph of  
apparatus.

diagram consisting of four units each including energy storage capacitor  $C$ , inductance  $L_0$ , resistance  $R_0$ , multichannel arc spark gap switch  $G$  [10] and circuit for triggering switch  $G$  by mutual induction, and one load of  $L_0$  and  $R_0$ , which represent the inductance and the resistance of the electrode-and-workpiece section. The capacitor bank typically consists of eight  $100\text{-}\mu\text{F}$  capacitors parallel to each other, and each multichannel arc spark gap switch  $G$  with inductance below  $10\text{ nH}$  having four arc channels is used for two of the capacitors. The inductance  $L_0$  and the resistance  $R_0$  of the four units of capacitor, switch and transmission line are  $7.2\text{ nH}$  minimum and  $0.90\text{ m}\Omega$  minimum, respectively.

Fig. 3 shows the electrode-and-workpiece section of the apparatus. An inner electrode 3 is inserted in a metal workpiece 4, an insulating tube 2 being placed between them. The workpiece is in close contact with the outer electrode 1 and the inner one 3 at its ends with usual bolt joints. The discharge current flows in the direction of the arrows from the outer electrode toward the inner electrode through the workpiece. The current flowing through the workpiece has the opposite direction to that flowing through the inner electrode, and repulsing force between them can bulge the workpiece as shown by the dotted lines in the figure. The electrodes are made of copper, and the diameter  $D$  of the inner one can be chosen from 38.5, 30.0 and 20.0 mm. The workpiece of aluminum (A1050TD) annealed one hour at  $400^\circ\text{C}$  has a thickness  $0.50\text{ mm}$  and an outer diameter  $d_0=40.0\text{ mm}$ . In our experiments almost no erosion was found on the workpiece surfaces contacting with the electrodes. The calculated values of the inductance  $L_0$  and the resistance  $R_0$  are very low as shown in Table 1.

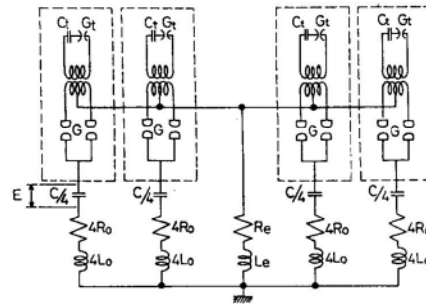


Fig.2 Discharge circuit.  
 $G$ =gap switch,  $G_t$ =trigger capacitor,  $C$ =energy storage capacitor,  $E$ =charged voltage;  $L_0$ ,  $L_e$ =inductance;  $R_0$ ,  $R_e$ =resistance.

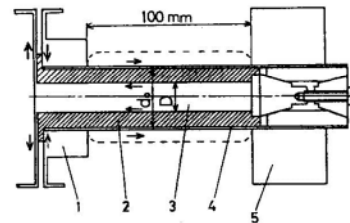


Fig.3 Cross-section of electrode-and-workpiece section.  
1=outer electrode, 2=insulating tube, 3=inner electrode, 4=workpiece, 5=tube holder.

Table 1 Inductance  $L_0$  and resistance  $R_0$  of electrode-and-workpiece section.

$D/\text{mm}$	$L_0/\text{nH}$	$R_0/\text{m}\Omega$
20.0	0.91	0.20
30.0	0.88	0.16
38.5	0.87	0.14

If the gap switches are closed at time  $t=0$  and all the charged energy  $CE^2/2$  is discharged at  $t=t_m$ , the rate of the energy passing from the charged energy to the magnetic energy in the electrode-and-workpiece section is given by

$$\frac{\frac{1}{2} L_e i^2(t_m)}{\frac{1}{2} C E^2} = \frac{L_e}{L_o + L_e} \left[ 1 - \frac{\int_0^{t_m} (R_o + R_e) i^2(t) dt}{\frac{1}{2} C E^2} \right] \quad (1)$$

where  $i(t)$  is the discharge current. The maximum rate obtained in the apparatus is 0.11.

The waveform of the discharge current is obtained with a search coil or a Rogowski coil. The form of bulged workpieces is determined with a contracer.

## 2.2 Results and Discussion

We mention the discharge current flowing through a workpiece. During bulging,  $L_o$  and  $R_e$  of the electrode-and-workpiece section change with the deformation of the workpiece. Their changes are smaller than the inductance  $L=L_o+L_e$  and resistance  $R=R_o+R_e$ , respectively, of the circuit. The discharge current is approximately expressed by

$$i(t) = \frac{2E}{\sqrt{(4L/C) - R^2}} \exp(-Rt/2L) \sin \left[ \sqrt{(4L/C) - R^2} / 2L \right] t \quad (2)$$

Fig. 4 shows the example of the current waveforms which are obtained by varying the diameter  $D$  of the inner electrode at a charged energy of 5 kJ. As the diameter decreases,  $L_o$  and  $R_e$  increase, causing the current given by Eq. (2) to decrease and the period to increase. The maximum current  $i_{max}$  (810 kA at 5 kJ) and the charged energy change with the diameter  $D$  as shown in Fig. 5, where it is seen that the maximum current increases with the increasing charged energy and the diameter  $D$ .

It is assumed that discharge current flows symmetrically with respect to the axis in the middle of the workpiece. Under this condition, the magnetic field  $B$  and the magnetic pressure  $B^2/2\mu$  inside

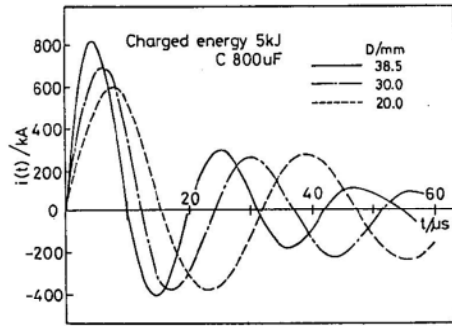


Fig. 4 Waveforms of current  $i(t)$ .

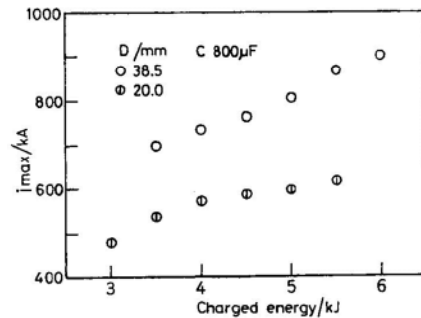


Fig. 5 Change of  $i_{max}$  and charged energy with inner electrode diameter  $D$ .

the workpiece are expressed in Eq. (3), the latter being in proportion to the square of the current:

$$B = \frac{\mu i(t)}{\pi d_i(t)}, \quad \frac{B^2}{2\mu} = \frac{\mu i^2(t)}{2\pi^2 d_i^2(t)} \quad (3)$$

where  $\mu$  is the permeability, and  $d_i(t)$  is the workpiece inside diameter. When the current was 810 kA maximum and the inside diameter was 39 mm minimum at 5 kJ, the magnetic field and magnetic pressure reached 8.3 T and 27 MPa, respectively.

Fig. 6 shows the change of bulge form with the diameter  $D$  of the inner electrode at 5 kJ, where  $\Delta r$  is the increase in tube radius and  $x$  is the axial distance from the middle of the bulged workpiece. As the diameter  $D$  decreases, the current and magnetic pressure decrease, reducing deformation. When the diameter  $D$  is 38.5 mm, the

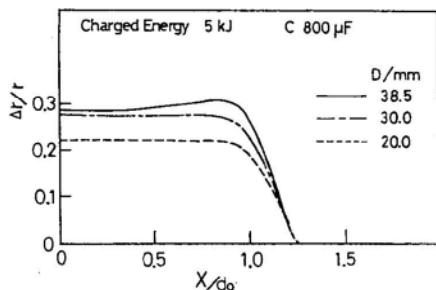


Fig.6 Partial shapes of bulged workpieces.

maximum deformation is obtained at the one end of the workpiece into which current is introduced unequally. As the diameter  $D$  decreases, the deformation curve becomes flatter and more gradual. Fig. 7 shows the change of  $\Delta r$  in the middle of the workpiece and the charged energy with the diameter  $D$  of the inner electrode. As the charged energy and  $D$  increase,  $\Delta r$  grows. When  $C$  and  $D$  were  $800 \mu\text{F}$  and  $38.5 \text{ mm}$ , respectively, at  $5.5 \text{ kJ}$ , the workpiece cracked.

Now we explain the effects of the bank capacity  $C$  on the current and bulging. The current waveforms are obtained at  $C=200 \mu\text{F} \times 4=800 \mu\text{F}$  and  $C=100 \mu\text{F} \times 4=400 \mu\text{F}$ , both being discharged through the four units in parallel in Fig.1. The waveform at  $C=800 \mu\text{F}$  is larger than that at  $C=400 \mu\text{F}$ , because using one capacitor in each unit at  $C=400 \mu\text{F}$  results in  $L_e=9.0 \text{ nH}$  and  $R_e=1.1 \text{ m}\Omega$ , which are larger than those at  $C=800 \mu\text{F}$ , while the period of waveform at  $400 \mu\text{F}$  is shorter. The maximum current  $i_{\text{max}}$  at  $C=800 \mu\text{F}$  are higher than at  $C=400 \mu\text{F}$ , though a considerable difference between them is not seen. The comparison of the increase in tube radius  $\Delta r$  is shown in Fig. 8: the increase at  $800 \mu\text{F}$  is larger by about 50%.

Fig. 9 shows the increase in tube radius  $\Delta r$  when two or four capacitor-and-switch units are used in parallel. We had made an experiment with two units at  $C=400 \mu\text{F} \times 2=800 \mu\text{F}$ , obtaining  $L_e=12 \text{ nH}$  and  $R_e=1.7 \text{ m}\Omega$ , as reported elsewhere [9]. At each charged energy,  $\Delta r$  with four units is larger than with two units, which can be ex-

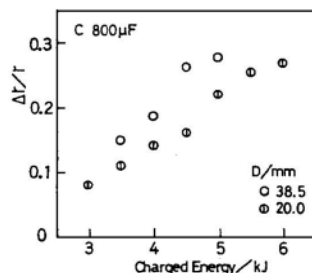


Fig.7 Change of  $\Delta r/r$  and charged energy with inner electrode diameter  $D$ .

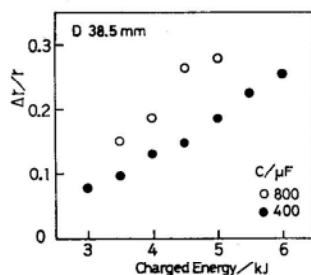


Fig.8 Change of  $\Delta r/r$  and charged energy with capacity  $C$ .

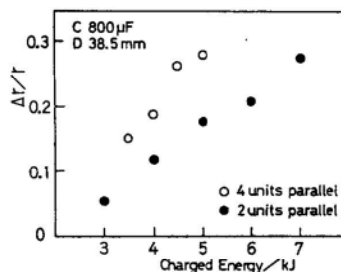


Fig.9 Change of  $\Delta r/r$  and charged energy with number of units in parallel.

plained by the fact that the magnetic energy transferring into the electrode-and-workpiece section of the discharge circuit with four units is larger due to less inductance  $L_e$  and resistance  $R_e$  of the units. As a result, the lower the inductance and resistance of the units are, the higher the current flowing through the electrode-and-workpiece section and the magnetic pressure working on the workpiece become.

On the basis of the experimental results, we should consider the following points for efficiently bulging metal tubes by the direct electrode contact method:

- 1) using capacitors and switches with a low inductance, which are arranged in parallel to reduce the inductance and resistance of the discharge circuit, and
- 2) increasing the diameter of the inner electrode.

### 3. Bulging by the Solenoidal Coil Method

#### 3.1 Solenoidal Coil

A forming solenoidal coil with an inductance of  $14 \mu\text{H}$  is 3.0 mm in pitch, 120 mm in length, 37.0 mm in outside diameter. It is covered with an insulating sheet, on which is put the workpiece. For the experiment was used the same capacitor bank, gap switches and workpiece as those described in Chapter 2. The load of  $L_0$  and  $R_0$  in Fig. 1 is replaced with a solenoidal coil. When a discharge current flows from the capacitor bank to the coil, the workpiece can be bulged.

When the coil is inserted in the workpiece, its inductance reduces equivalently to  $3 \mu\text{H}$ , which is still much larger than the inductance  $L_0$  of the capacitor-and-switch units. Most of the charged energy of the capacitor bank transfers to the coil by Eq.(1). Though the inductance  $L_0$  changes with the capacity of the bank, the change affects the results of bulging very little.

#### 3.2 Results and Discussions

Magnetic pressure acting on the workpiece inside wall is in proportion to the square of the discharge current  $i(t)$ . If the skin depth of the workpiece for the magnetic field is smaller than the wall thickness, the magnetic pressure is approximately given by

$$\frac{B^2}{2\mu} = \frac{\mu d_0^2 i^2(t)}{2p^2 d_i^2(t)} \quad (4)$$

where  $d_0$  is the coil diameter,  $p$  is the coil pitch, and  $d_i(t)$  is the inside diameter of the workpiece.

Fig. 10 shows the change of  $i(t)$  waveform with the capacity  $C$  at a charged energy of 0.8 kJ. As  $C$  decreases, the period shortens, while the maximum current  $i_{\max}$  increases. Though a maximum of 28 kA is obtained at  $C=50 \mu\text{F}$ , this value is considerably smaller than by the direct electrode contact method, which is due to not only the small charged energy but the much higher equivalent inductance of the solenoidal coil than that of the discharge circuit by the direct electrode contact method. Fig. 11 shows the change of the maximum current  $i_{\max}$  and the angular frequency  $\omega$  with the capacity  $C$ .  $\omega$  was calculated from the first half period of the current waveform. As  $C$  decreases, both  $i_{\max}$  and  $\omega$  increase.

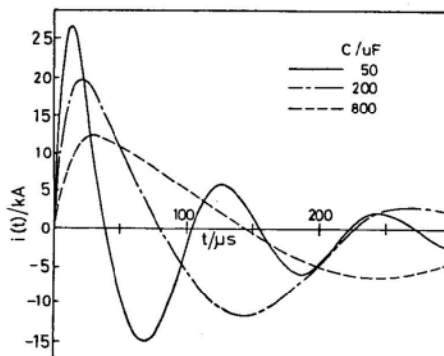


Fig.10 Waveforms of current  $i(t)$ .

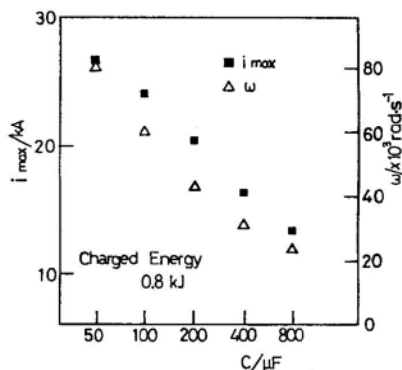


Fig.11 Change of maximum current  $i_{\max}$  and angular frequency  $\omega$  with capacity  $C$ .

Fig. 12 shows the forms of workpieces bulged by the solenoidal coil method, in which  $\Delta r$  is the increase in tube radius and  $x$  is the distance from the middle of the workpiece. Due to free expansion, the beginnings of deformation (right) are more gradual than those in Fig. 6. As the capacity  $C$  decreases,  $\Delta r$  increases.  $C$  and  $\Delta r$  change with charged energy as shown in Fig. 13. Workpieces cracked, when bulged with  $C=50$  or  $100 \mu\text{F}$  at a charged energy of  $1.0 \text{ kJ}$ . As  $C$  increases,  $\Delta r$  decreases, which is due to the following fact: as  $C$  increases, (1)  $i(t)$  decreases, and (2) both  $\omega$  and the magnetic pressure decrease, while the skin depth increases.

In bulging by the solenoidal coil method, it is necessary to estimate the skin depth. When the capacity  $C$  is  $200 \mu\text{F}$  or below, the skin depth is  $1 \text{ mm}$  or less, which leads to the comparatively little difference in deformations.

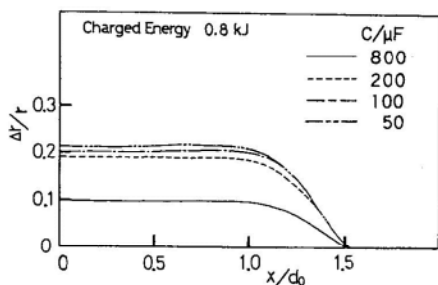


Fig. 12 Partial shapes of bulged workpieces.

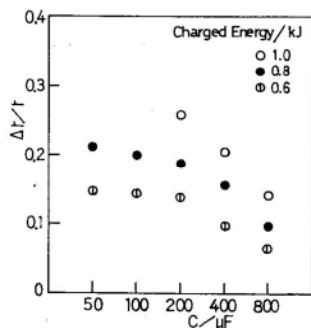


Fig. 13 Change of  $\Delta r/r$  and capacity  $C$  with charged energy.

#### 4. Conclusion

We made a new experiment of the electromagnetic bulging of metal tubes by the direct electrode contact method, in which an extremely low inductance of the electrode-and-workpiece section makes low the rate of the charged energy transferring from the capacitor bank to the electrode-and-workpiece section. The inductance of the capacitor-and-switch units also affects the results of bulging considerably.

For comparison we made an experiment by the conventional method, i.e. the solenoidal coil method. To obtain the same bulges the direct electrode contact method needs a charged energy as much as five times.

In order to increase the energy efficiency of the capacitor bank in the direct electrode contact method, it is necessary to still lower the inductance of the said units and to raise the inductance of the electrode-and-workpiece section by using longer workpieces to be bulged.

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