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Fundamental Study on Electrohydraulic Forming*

(III. The Effect of Diameter of Fuse Wire and Circuit Inductance on Pressure Pulse)

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There have been many studies on electrohydraulic forming in which the deformation characteristics of metallic material are investigated. In most of the studies the wires used as pressure source were very fine. A clear-out account has not been given of the relationship between the dimensions of wires and the initial discharge circuit conditions such as capacitor voltage and circuit inductance, and then for a given stored electrical energy there have been few studies showing what kinds and dimensions of wires to use as effective pressure source.

By the reason of F.H. Webb's experimental fact that, when sufficient energy is placed in a wire to vaporize it, the delaying time of boiling is of the order or less than the time required for a sonic wave to traverse the wire at boiling temperature, the longer the delaying time, the higher will be superheating.

This paper presents the results of experiments where a capacitor discharge circuit for an electrohydraulic forming machine is used to explode a fine copper wire, diameter of which is 0.14 to 0.40 mm. The best condition for creating a pressure pulse is investigated and discussed.

1. Introduction

In the previous paper the authors have investigated the influences of the charged energy on the amplitude of the pressure pulse and its shape when an aluminum, copper or tungsten wire, 0.20 mm in diameter and 5 cm in length, is exploded. There have been many studies on electrohydraulic forming in which the deformation characteristics of metallic material are investigated. Most of the studies have been carried out with wires of comparatively small diameter about 0.20 mm even for a high energy level.

A clear-out account has not been given of the reason as to what kinds and dimensions of wires to use as effective pressure source, but those wires are merely used in order to investigate the deformation characteristics of metallic material of a given shape.

According to the result of F.H. Webb's⁽¹⁾ experimental data, the delaying time until boiling is equal to the time required for a sonic wave to

propagate across the diameter of wire. If such fact is true, it can be assumed that an effective pressure pulse will be obtained by a method using a wire of large diameter and high energy level effectively. Such method has been investigated with an experimental apparatus of laboratory scale, having, for instance, a circuit inductance of the order of $10\mu\text{H}$. The apparatus satisfying this condition cannot be realized as an electrohydraulic forming machine.

This paper shows the relationship between the diameter of wire and the circuit inductance in the apparatus, and describes the characteristics of the discharge circuit used for a general electrohydraulic forming machine. The best condition for creating a pressure pulse is investigated.

2. Experimental apparatus and procedure

The circuit inductance is $4\mu\text{H}$ and $6\mu\text{H}$, and the electric gap is short-circuited by copper wires, 0.14, 0.20, 0.26, 0.32 and 0.40 mm in diameter and 2.5, 5.0 and 10 cm in length. Otherwise, the conditions are the same as those of the previous experiments.

3. Experimental results

When copper wires, 0.14 to 0.40 mm in

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diameter and 2.5, 5.0 and 10 cm in length, are exploded with various charged energy and inductance, the shapes of the pressure pulse are similar to those in the previous experiment for copper wires, the rise time of pressure pulse is about $4\mu\text{sec}$ and its duration is about $10\mu\text{sec}$. In Fig. 1 is shown the relationship between the pressure ratio and the

Fig. 1 Relationship between pressure ratio and length of copper wire in case of constant charged energy 190, 430 and 780 joules

Fig. 2 Relationship between charged energy and pressure ratio
 $L=4\mu\text{H}$, Parameter: diameter of wire

length of wires, the parameter being the charged energy per unit length when the circuit inductance is $6\mu\text{H}$. It becomes evident that the pressure ratio does not depend on the charged energy, but on the charged energy per unit length. In Fig. 2 is shown the pressure ratio against the charged energy for $4\mu\text{H}$, the parameter being the diameter of wire.

Fig. 3 Relationship between charged energy and pressure ratio
 $L=6\mu\text{H}$, Parameter: diameter of wire

Fig. 4 Relationship between diameter of wire and pressure ratio
Parameters: charged energy and inductance

When the diameter of wires is small, the rate of increase in the pressure ratio becomes small with an increase in the charged energy. At the constant charged energy the magnitude of the pressure pulses turns out widely different according to the diameter of wire. The influence of its diameter is remarkable at a high energy level.

In Fig. 3 is shown the pressure ratio against the charged energy per unit length. The rate of increase in the pressure ratio for $6\mu\text{H}$ is smaller than one for $4\mu\text{H}$. In the range of small diameter of wire the magnitude of the pressure pulses for $6\mu\text{H}$ is large at various energies. At the high energy level the influence of the charged energy on the diameter of wire is not so remarkable as that for $4\mu\text{H}$. This result is presented clearly in Fig. 4, in which the relationship between the diameter of fine wires and the pressure ratio is shown, the parameter being the charged energy per unit length. The solid and dotted lines show the relation for $4\mu\text{H}$ and $6\mu\text{H}$, respectively. At the charged energy below 84 J/cm there is an optimum diameter of wire for each of the pressure pulses. The optimum value shifts to larger diameters with an increase in the charged energy as shown in the previous paper⁽²⁾. This tendency may be due to the small increase in superheating because of the decrease in energy per volume. At the low energy level a larger value of pressure

appears for $6\mu\text{H}$. When the charged energy increases furthermore, a higher pressure value is obtained for $4\mu\text{H}$ than for $6\mu\text{H}$ and with an increase in the charged energy this tendency occurs at a smaller diameter of wire. The reason why a fairly high value pressure pulse is obtained for $4\mu\text{H}$ and at a high energy level is the high rate of energy supply and high superheating.

4. Energy of pressure pulse, efficiency and discussion

The shapes of the pressure pulse are independent of the circuit inductance, the charged energy and the diameter of wires, being very similar to those in the case of a copper wire being exploded as shown in the previous paper. The energy of the pressure pulses can be calculated from the pressure ratio. When Eq. (8) in the previous paper is used, the energy of the pressure pulses E_p is given by Eq. (1)

$$E_p = 4.4A^2 \dots\dots\dots (1)$$

A : pressure ratio

In Fig. 5 is shown E_p calculated from Eq. (1), where the parameters are the diameter of wire and the circuit inductance. As E_p is proportional to the square of the pressure ratio, the energy of the pressure pulse increases to a high value at the high energy level of 280 J/cm under the influences of the circuit inductance and the diameter of wire. In Fig. 6 is shown the relationship between the charged energy and the efficiency, the parameters being inductance and the diameter of wire. The efficiency is defined as follows

$$\text{Efficiency} = \frac{E_p}{\text{charged energy}[(1/2)CV^2]} \times 100(\%) \dots\dots\dots (2)$$

Parameters: diameter of wire and inductance
Fig. 5 Charged energy and energy of pressure pulse

Parameters: diameter of wire and inductance
Fig. 6 Relationship between charged energy and efficiency

At a low energy level the efficiency is high for diameters 0.20 and 0.26 mm and for $6\mu\text{H}$. The influences of the circuit inductance and the diameter of wire on the efficiency become evident with an increase in the charged energy. In Fig. 7 is shown the relationship between the diameter of wire and the efficiency, the parameters being the charged energy and circuit inductance. At 38 J/cm and 86 J/cm there exists an optimum diameter of wire for which maximum efficiency is obtained. At higher energy levels, $4\mu\text{H}$ is better in efficiency and as the charged energy increases, there is an also optimum value of the diameter of wire.

From F.H. Webb's⁽¹⁾ experimental result that the delaying time until boiling is equal to the time required for a sonic wave to propagate the diameter of wire, the delaying time of boiling is constant when the diameter of wire is constant and the charged energy is sufficiently large to vaporize the wire. If the circuit inductance is made small or the diameter of wire made large in this case, superheating increases during the delaying time. From this fact it may be understood that the optimum efficiency is obtained for a large diameter of wire and a small circuit inductance.

In Fig. 8 is shown the summary data of the results described. In the figure the vertical axis represents the efficiency and the horizontal axis

Parameters: charged energy and inductance

Fig. 7 Relationship between diameter of wire and efficiency

does the charged energy per unit volume of wire. The oblique curve of hyperbola represents the charged energy per unit length. The solid and dotted lines are the curves for $4\mu\text{H}$ and $6\mu\text{H}$, respectively. The straight lines which pass through the origin in the figure are the lines for the same diameter of wire. In spite of the increase in the charged energy per unit volume an increase in efficiency does not occur for small diameters. It can be concluded that at the constant charged energy per unit volume the efficiency is improved with an increase in the charged energy per unit length and the diameter of wire.

5. Conclusion

Since the relations among the diameter of wire inserted at the electric gap as the pressure source, its length and the charged energy has not been made clear, the authors studied those relations, including the influences of circuit inductance.

From above investigations the authors have reached the conclusions as follows.

(1) In the case of a copper wire the shapes of pressure pulse are independent of the circuit inductance and the diameter of wire. The rise time of pressure pulse is about $4\mu\text{sec}$, its duration being about $10\mu\text{sec}$.

(2) At high energy levels and large wire diameters the circuit inductance has an extremely large influence on the magnitude of pressure pulse.

(3) When the charged energy to vaporize the wire is sufficiently large, the larger pressure pulse occurs for the larger diameter of wire and the efficiency also becomes the higher.

Fig. 8 Relationship between charged energy per volume and efficiency

(4) At low energy levels there exists a diameter of wire for which the value of maximum pressure pulse is obtained.

On the basis of these data the authors have investigated the deformation characteristics of metallic material. A detailed report will be published in the near future.

The authors have presented a series of studies on the pressure pulse created by the electrohydraulic discharge in water. They believe that these presentations of the results of investigation will provide the readers with a better understanding of

the general capabilities of the electrohydraulic effect, and that the information presented may be of some use in the future design of equipment for an electrohydraulic forming machine.

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