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Pressure Pulses Produced by Underwater Wire Explosions in Electric Discharge Metal Forming*

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The impulsive pressure pulses arising from copper wire explosions are measured using Hopkinson pressure bar technique under various charging voltages up to 63 kV, charging energies up to 2.6 kJ, natural frequencies of the discharge circuit from 10 kHz to 50 kHz and various wire dimensions, and impulses which are defined as time integral of the pressure pulse are obtained. The decays of a pressure pulse and an impulse during propagation are represented by the ratio of stand-off distance to length of the wires. Taken together with the previous paper, the dependencies of peak values and impulses of the pressure pulses upon the energies consumed in exploding wires are obtained. It is also shown that, when charging energies are held constant, low voltage (and thus large capacity) and high voltage (and thus small capacity) are equally efficient provided that the optimum wire dimensions are chosen for each case.

1. Introduction

For quantitative understanding of the electric discharge metal forming, it may be important to characterize the pressure pulses produced by underwater wire explosions. The pressure pulses can be classified into two kinds: the primary pulse caused by the wire explosion and the secondary pulse caused by the vibration or collapse of cavities produced by the explosion. Although Yamada⁵⁾ and Nishiyama⁶⁾ recently reported that the secondary pulse sometimes plays an important role in the forming, the primary pulse is more essential when examining the relation between the intensity of the pulse and the energy consumed in exploding wires.

The measurement of the primary pressure pulse has been reported by Oyane³⁾, Yamada⁷⁾ and O'kun⁴⁾. However, the relation between the primary pressure pulse and conditions of discharge has yet been obscured.

In the previous paper⁸⁾, the authors have clarified the quantitative relations between the energy consumed at the gap during wire explosion and both the conditions of the discharge circuit and the wire dimensions. The purpose of the present paper is to ascertain the relation between the energy consumed and the intensity of the primary pressure pulse. When taken together, the present and previous papers will provide a more precise understanding of the pressure pulses in connection with the conditions of the discharge circuit and the wire dimensions.

2. Experimental Apparatus and Conditions of Experiment

The experiments were carried out at various levels of initial energy E_0 stored in the capacitor bank, and at various values of cross sectional area s_w and length l_w of the copper wire bridging the gap as shown in Table 1. The current in discharge is measured by a Rogowski coil connected to an RC integrator. The voltage across the gap is measured by a resistance voltage divider. The inductance of the discharge circuit is about 7.5 μ H. Further details concerning measurements of the current and voltage are available in the previous paper. The pressure pulses are detected by a Hopkinson pressure bar mentioned in the following section.

Table 1 Conditions of discharge

E_0 kJ	C_0 μ F	V_0 kV	f_0 kHz	R_c^* Ω	wire dimensions
2.6	1.25	63	53	0.18	material :copper
	2.5	45	37	0.1	
	4.6	34	27	0.08	
1.3	1.25	45	53	0.18	$S_w = 0.025$ $\sim 0.25 \text{ mm}^2$ ($n_w = 1 \sim 10$) $n_w = 1 : 0.025 \text{ mm}^2$ $l_w = 40 \sim 200 \text{ mm}$
	2.5	32	37	0.1	
	4.6	24	28	0.08	
	40	8.4	9.4	0.04	
0.65	1.25	32	53	0.18	$S_w = 0.029, 0.067,$ 0.12 mm^2 ($\phi_w = 0.193, 0.293,$ 0.391 mm) $l_w = 40 \sim 100 \text{ mm}$
	2.5	22.6	37	0.1	
	4.6	16.6	28	0.08	
	40	5.9	9.4	0.04	
0.85	5.8	17.2	26	0.05	

E_0 :charging energy, C_0 :capacitance of capacitor bank, V_0 :charging voltage, f_0 :natural frequency of discharge circuit, R_c^* :resistance of the circuit without wired gap, s_w :cross sectional area of wires, l_w :length of wires, n_w :number of wires, ϕ_w :wire diameter.

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3. Preliminary Examinations of Pressure Pulse Measurement by Pressure Bars

Fig.1 illustrates pressure bar I and the bridge circuit of strain-gages used for the measurements of pressure pulses. When the pressure pulse arrives at an immersed end of the pressure bar, a corresponding elastic wave occurs. The elastic wave propagates in the pressure bar and is detected by the strain gages attached at an appropriate distance from the end of the bar. By determining the delay time in the propagation of the elastic wave from the end to the strain gages, a precise measurement of the pressure pulse can be made without being affected by the electro-magnetic and static effects during the discharge. In order to get large output voltage signals, semiconductor strain gages of $2\text{ k}\Omega$ are used. A couple of gages connected in series constitute one element of the bridge circuit. The output signals are directly measured by an oscilloscope. The layout of the pressure bar is illustrated in Fig. 2. It is placed in a water bath perpendicular to the wire. A rubber sheet is inserted in the supporting rig, so as to avoid the distortion of the signals caused by the support. The stand-off distance L_D from the wire to the end of the bar is 100 mm unless otherwise specified. Signals output by the bar are calibrated by two different methods. One is a bending method and the other is a method where the stress wave produced by striking one end of the bar with another bar is compared with the theoretical one.

A supplementary experiment in which the lateral part of the bar is covered so that the pulse can be detected only from the immersed end shows there is no difference in wave shapes with and without the cover. Therefore the cover is not used in the following experiments.

Various traces of the pressure pulse reported in previous works seem to depend not only on the experimental conditions but also on the method of measuring the pulse. In some cases, for example, the pulse trace is damped exponentially with a rise time of $2\text{ }\mu\text{s}$ and a duration of $40\text{--}50\text{ }\mu\text{s}$. In other cases, it is nearly damping oscillation. Such differences in the pulse trace may be attributed not only to differences in the conditions of a discharge circuit and wire dimensions, but also to differences in the detecting elements and their setting conditions.

Special care must be taken regarding the response characteristics of the detecting elements of the pressure pulse. When measuring a pressure pulse with a pressure bar, it is assumed that the elastic wave propagates in the bar with no distortion. In reality, of course, the elastic wave is distorted because the radial inertia and the viscosity of the bar affect the propagation of the elastic wave. It has been shown by Davies⁽²⁾ that the effect of the radial inertia is significant in waves

Fig.1 Pressure bar I and bridge circuit

Fig.2 Layout of pressure bar

(a) wave by knocking with a hammer ($l_b=2000\text{ mm}$, $l_g=1500\text{ mm}$)

noise caused by discharge

(b) wave by a wire explosion ($l_b=2000\text{ mm}$, $l_g=1000\text{ mm}$, $C_0=1.25\text{ }\mu\text{F}$, $V_0=45\text{ kV}$, $s_w=0.1\text{ mm}^2$, $l_w=60\text{ mm}$, $L_D=100\text{ mm}$)

Fig.3 Decay of elastic waves in pressure bar I (vertical scale: $69\text{ kgf/cm}^2/\text{div}$, horizontal scale: 0.5 ms/div)

Table 2 Specifications of the pressure bars

bar	ϕ_b mm	l_b mm	l_g mm	R_g Ω	V_B V	output $\text{kgf/cm}^2/\text{V}$
I	8	1500	500	2000	45	1.1×10^3
II	20	2000	500	2000	22.5	1.26
III	8	1500	25	120	6	11.5
			500	120	6	11.6
IV	3	500	20	120	6	10.3
			200	120	6	11.4

whose wavelength is small compared with the diameter of the bar.

The traces of waves produced in the bar by (a) knocking its end with a hammer, and by (b) an underwater wire explosion are shown in Fig.3. In both cases, the elastic wave runs forth and back between the ends of the bar and decays gradually. The damping rate of the wave is greater for (a) than for (b). The difference in the damping rate may be explained as follows: The elastic wave in case (a) is composed of low-frequency components; while in (b), of components having higher frequencies. The higher frequency components attenuate more rapidly than the lower ones. For this reason, the wave trace decays easily for the explosion. We must note that if we want to obtain quantitative informations of the pressure pulse, a shape correction for the elastic wave signal is indispensable.

To find the correcting method, the preliminary experiments were carried out, where the various pulse shapes detected by different sizes of pressure bars and at various positions of the strain gage on the bars were examined. Table 2 provides details of the bars used.

Fig.4 compares the shapes of the pulse measured by bar III; the distance L_G between the end of the bar and the strain gage being 25 and 500 mm respectively. The shape of the pulse for $L_G=25$ mm is almost triangular with a rise time of 1.5 μ s, a

Fig.4 Example of pulse shape deformation (bar III)

Fig.5 Damping of p_m during propagation in pressure bars (p_e : value of p_m extrapolated up to $L_d=0$)

peak height value of 500 kgf/cm² and a duration of 12 μ s. The shape for $L_G=500$ mm is deformed into exponential flare out with a rise time of 7 μ s, a peak value of 420 kgf/cm² and a duration of 25 μ s. Similar deformation of the pulse shape is observed with other bars; the degree of deformation increases with increase of the diameter of the bars.

Fig.5 illustrates the peak values versus total length L_d which the elastic wave travels in the bar, for each of the cases shown in Table 2. In the figure the peak value is normalized by the peak value p_e which is obtained by extrapolating the data points to $L_d=0$; the values of p_e are also shown in the figure. It can be seen that the values of p_m/p_e for bars III and IV decrease rapidly near the end of the bar. The reason may be that the elastic wave which occurs in a bar with a large diameter can be rapidly deformed into the shape which is made up only from low frequency components, and after the deformation of the wave shape, the damping rate of the wave is deruced. The difference in the damping rate for waves observed in bars I and III which have the same diameter may be attributed to the difference of the data points in extrapolation; the data are extrapolated up to $L_d=0$ by a straight line. When the value of L_G is taken as 20 and 25 mm for bars III and IV, the relative error due to the extrapolation is only 1-2%.

Fig.6 Peak p_m and impulse F_t of pressure pulse measured by bars I, II, III, IV (line is obtained from data without bar II)

It is preferable to set the strain gage near the end of the bar, so as to reduce the wave shape deformation as far as possible. In the following discussion, the shape of the output signal of bar I is corrected with the aid of the wave shape measured by strain gages attached on bars III and IV at the above-mentioned positions.

The pressure pulse caused by the explosion is characterized both by the peak value p_m and by the impulse F_t defined by

$$F_t = \int_0^{t_p} p dt \quad (1)$$

where t_p represents the time at which the pressure becomes 1/10 of the peak value. Under the same experimental conditions, values of p_m and F_t were obtained by bar I (case A) and bars III and IV (case B). The results of p_m and F_t in cases A and B are compared in Fig. 6. The solid line in the figure is determined by the least squares method. It is seen from the figure that the ratio of p_m values between the two cases is 1/2.2 and that of F_t is 1/1.

Let us consider the reason why p_m varies between the two cases by a factor of 2.2. Fig. 7 depicts a circuit equivalent to the bridge circuit illustrated in Fig. 1. The output voltage ΔV of this circuit caused by the infinitesimal change in re-

Fig. 7 A circuit equivalent to the bridge circuit shown in Fig. 1

Fig. 8 Simplified equivalent circuit

Fig. 9 Shape correction of a pressure pulse using Eq. (3)

sistance ΔR_B of the semiconductor strain gage is given as

$$\Delta V = -V_B \frac{\Delta R_B}{4R_B} \frac{1}{1 + R_B C_K \omega i} \quad (2)$$

which indicates that the output is reduced by a factor of $1/(1 + R_B C_K \omega i)$ due to the capacitance of the coaxial cable used here. The effect of reduction is represented by the equivalent circuit shown in Fig. 8. The time constant $\tau = R_B C_K$ of the equivalent circuit is only 0.3 μs in case B. In case A it becomes 5 μs , which cannot be ignored in the measurement of the pressure pulses. The relation between input ΔV_i and output ΔV can be expressed by

$$\Delta V_i(t) = R_B C_K \frac{d[\Delta V(t)]}{dt} + \Delta V(t) \quad (3)$$

where $\Delta V_i(t)$ corresponds to the output of which the value would be $-V_B \Delta R_B / 4R_B$ if the coaxial cable had no capacitance. Introducing the measured values of the output ΔV into Eq. (3), a corrected output $\Delta V_i(t)$ is obtained. The pulse shapes before and after the shape correction mentioned above are compared in Fig. 9; the pulse is detected by bar I. In the figure, the corresponding data by bar III are also shown, which has the least wave deformation due to the effect shown in Fig. 8. It can be seen from the figure that the corrected shape of the pulse by bar I almost coincides with that by bar III. Based on the above consideration, it may be concluded that the deformation of the wave is also caused by the capacitance of the coaxial cable used in the experiment. Integrating Eq. (3) with respect to time, we obtain

$$\int_0^t \Delta V_i(t) dt = R_B C_K \Delta V(t) + \int_0^t \Delta V(t) dt \quad (4)$$

Here, the left-hand term of the equation indicates the true impulse of the wave and the second term of the right-side denotes the apparent impulse. Integrating eq. (4) to t_p when $\Delta V(t)$ is small enough, the apparent impulse coincides with the true impulse.

In most of the experiments in the paper, the pressure pulses were measured by bar I, because measurements by bars III and IV, in which output signals are very small, is sometimes hindered by the noise induced at discharge. The values of p_m measured by bar I are corrected based on the results in Fig. 6.

4. Pressure Pulse and Energy Consumed at Gap during Explosion

The oscillograms of pressure pulses for various wire dimensions s_w and l_w are illustrated in Fig. 10. The traces are triggered after 150 μs from the initiation of discharge since it takes about 170 μs for the pressure pulse to reach the strain gages. The traces of the discharge current I are also shown in the figure. The peak value p_m and the impulse F_t obtained from the traces in Fig. 10 are illustrated in Fig. 11, where the values of p_m are 2.2

Fig. 10 Measured pressure pulses and currents ($C_0=1.25 \mu\text{F}$, $V_0=45 \text{ kV}$)
(pulse: $110 \text{ kgf/cm}^2/\text{div}$, $10 \mu\text{s}/\text{div}$. current: $14 \text{ kA}/\text{div}$, $2 \mu\text{s}/\text{div}$)

Fig. 11 Dependence of peak p_m and impulse F_t of pulse on wire dimensions s_w , l_w ($C_0=1.25 \text{ F}$, $V_0=45 \text{ kV}$)

Fig. 12 Relation between W_I and p_m ($l_w=80 \text{ mm}$)

times those in the oscillograms. It can be seen that the maximum of p_m (480 kgf/cm^2) occurs at $s_w=0.05 \text{ mm}^2$ and $l_w=90 \text{ mm}$, and that the maximum of W_I ($3.4 \times 10^{-3} \text{ kgf s/cm}^2$) occurs at $s_w=0.05 \text{ mm}^2$ and $l_w=130 \text{ mm}$. It is interesting to note the following facts. The cross sectional area $s_w=0.05 \text{ mm}^2$ at which p_m and F_t reach their maximum coincides with the area for which the energy W_I consumed at the gap is also at the maximum (refer to the previous paper⁸). The wire length $l_w=130 \text{ mm}$ for maximum F_t is not much different from the length $l_w=140 \text{ mm}$ for the maximum of W_I .

The relationship between W_I and p_m for $l_w=80 \text{ mm}$ is shown in Fig. 12. In the previous paper, the wire explosions were classified into three types: where the explosion occurs before a quarter of the period of the discharge current (type A), nearly at a quarter of the period (type B) and after a quarter of the period (type C). The data points circled by broken lines show the explosions in type C, which are a little below the other data points. This may relate to the fact that the duration of the explosion in type C is comparatively long so that the electric energy is consumed more moderately than in types A and B. In the following discussion, we examine the dependency of p_m and F_t on the consumed energy W_I for the explosions only in types A and B.

It has been shown that pressure pulses propagate in water depending on the length of the energy source (wire length in the present case) and the distance L_D from the energy source to the detector (end of the bar). Roughly speaking, the pulse becomes cylindrical for $l_w \gg L_D$ and spherical for $l_w \ll L_D$ ⁽¹⁾. Therefore, the pulse propagation depending on l_w and L_D is investigated at first. Fig. 13 shows the peak value and the impulse of pressure pulses for various values of l_w and L_D , where $\hat{p}_m$ and $\hat{F}_t$ denote p_m and F_t at $L_D=l_w$ respectively. The fig-

ure shows that the values of $p_m/\hat{p}_m$ and $F_t/\hat{F}_t$ are almost uniquely determined from L_D/l_w .

The relationships between $\hat{p}_m$ and W_I and between $\hat{F}_t$ and W_I are shown in Fig.14. The data points are slightly scattered and this may be attributed to the other factors such as rate of energy consumption during the wire explosion but it can be concluded that the values of $\hat{p}_m$ and $\hat{F}_t$ are determined by the ratio of W_I to l_w . In the previous paper, the effects of the various conditions

of the discharge on W_I have been obtained. When the previous results are combined with the present results shown in Figs. 13 and 14, the relation between the pressure pulse caused by the underwater wire explosion and the conditions of the discharge is understood. The procedure of the estimation of p_m and F_t is summarized as follows: First, the values of W_I is obtained from the known values of C_0 , V_0 , f_0 , s_w and l_w . Using the value of W_I/l_w obtained in the first step, the values of $\hat{p}_m$ and $\hat{F}_t$ are read from Fig. 14. And finally, the values of p_m and F_t can be found from Fig.13 with the aid of $\hat{p}_m$ and $\hat{F}_t$.

Fig.13 Decay of pressure pulse in water ($\hat{p}_m = p_m$ at $L_D = l_w$, $\hat{F}_t = F_t$ at $L_D = l_w$)

Fig.14 Dependency of p_m and F_t upon W_I/l_w

Table 3 Maximum values of impulse and peak of pulse and conditions under which they occur

charging condition			maximum of F_t and its dimensions			maximum of p_m and its dimensions			dimensions for maximum of η_I	
E_0 kJ	C_0 μF	V_0 kV	F_t^* kgs/cm ²	$S_w^* F_t$ mm ²	$l_w^* F_t$ mm	p_m^* kg/cm ²	$S_w^* p_m$ mm ²	$l_w^* p_m$ mm	S_w^* mm ²	l_w^* mm
2.6	1.25	63	—	0.05	—	—	0.05	—	0.075	—
	2.5	45	5.0×10^{-3}	0.087	160	610	0.087	120	0.10	160
	4.6	34	5.0	0.087	120	600	0.087	100	* 0.10	120
1.3	1.25	45	3.3	0.05	130	500	0.05	90	0.05	140
	2.5	32	3.3	0.05	160	470	0.05	80	0.075	110
	4.6	24	3.4	0.075	90	470	0.075	100	0.075	100
	40	8.4	3.4	0.15	80	490	0.15	80	0.15	80
0.65	1.25	32	1.8	0.05	100	300	0.05	100	0.05	100
	2.5	22.6	1.7	0.05	80	310	0.05	80	0.05	100
	4.6	16.6	1.8	0.05	80	350	0.05	80	0.05	80
	40	5.9	—	—	—	—	—	—	0.10	60

p_m^*, F_t^* : maximum values of peak p_m and impulse F_t of pulse

$S_w^* p_m, S_w^* F_t$: cross sectional areas for maximums of p_m and F_t

$l_w^* p_m, l_w^* F_t$: wire length for maximums of p_m and F_t

η_I : discharge efficiency defined by $\eta_I = W_I/E_0$

S_w^*, l_w^* : cross sectional area and length of wires for maximum of η_I

Arrows $\nearrow$ indicate that the values presented seem to be larger(smaller) than the actual one.

Fig.15 Maximums of peak and impulse, p_m^* , F_t^* , of pulse versus capacitance of the bank C_0 under various energies initially stored E_0

Let us now discuss the optimum condition of the discharge to maximize p_m and F_t . Table 3 shows the maximum values of p_m and F_t , and the corresponding wire dimensions for various charging conditions; the wire dimensions for the maximum of discharge efficiency η_I are also shown. It can be seen that the condition for the maximum of F_t and that for the maximum of η_I are almost same, and the wire length for the maximum of p_m is a little smaller than the one for the maximum of F_t .

In this forming, the effectiveness of the pressure pulse depends upon the impulse more significantly than on the detailed shape of the pulse, as the time of the deflection of a workpiece are usually much longer than the duration of the pulse. The optimum wire dimensions for η_I proposed in the previous paper are also available in the forming.

F_t decreases with an increase of L_D ; therefore, it seems advantageous to choose a small values of L_D . However, care must be taken is determining L_D , taking into consideration the size and shape of the workpiece. For a small L_D , the pressure of the pulse acting on it differs at positions on the surface of it. This causes uneven deformation.

It has been a serious problem for a long time whether to increase the capacity C_0 or the charging voltage V_0 , in order to get a high energy efficiency for pressure pulse formation. The results are shown in Fig.15. It may be concluded that the maximum values of p_m and F_t under fixed charging conditions are uniquely determined by the value of initial energy E_0 and do not depend on the combination of C_0 and V_0 as long as E_0 keeps constant.

5. Conclusions

The pressure pulses in water produced by the explosion of copper wires having various dimensions were measured by a Hopkinson pressure bar under charging energy levels $E_0 = 0.65, 0.85, 1.3$ and 2.6 kJ , various capacitor banks ranging from $C_0 = 1.25$ to $40 \mu\text{F}$ and natural frequencies of the discharge circuit ranging from 10 to 50 kHz. The relationships between both peak value p_m and impulse F_t of the pulse and energy W_I consumed during the wire explosion were clarified.

Conclusions are as follows:

1. The peak value and the impulse of the pulse depend on the ratio of the stand-off distance to the length of the energy source.
2. Dependences of both reduced peak and impulse of the pulse upon the ratio of W_I to wire length are obtained and illustrated in the figure.
3. The maximums of both p_m and F_t depend on E_0 and do not depend on the combination of C_0 and charging voltage V_0 .

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