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THE FORMING OF SHEET METAL USING AN UNDERWATER ELECTRICAL DISCHARGE I. Gilchrist* and B. Crossland**

INTRODUCTION

Soon after the Second World War, work was started on the use of high explosive to form metal sheet by using the pressure wave produced by the detonation of an explosive charge under water to force the sheet into a die.

The explosive nature of high energy electrical discharges across submerged spark gaps had been appreciated in the early development of oil immersed switchgear (for instance see Vogelsang (1)). It was not until 1953 however that use was made of this effect to form metal sheet, when Early and Dow (2) reported on the use of underwater discharges for blanking of sheet metal. In 1955 Yutkin (3) reported work on the bulging of tubes using successive electrical discharges. Since that time the interest in this method of forming has grown considerably (for instance see references (4) to (8)) and commercial electro-hydraulic forming machines are now available.

In 1962 work was initiated in the Queen's University of Belfast on the explosive forming of stainless steel dentures (9). This proved to be an accurate, simple and cheap method of their production. It was considered that electro-hydraulic forming would enable an automated process for manufacture of denture plates to be undertaken, and the work here reported originates from this interest.

Initial experiments with and without an "initiating" wire bridging the spark gap, and a review of the literature soon made it apparent that there was not a clear understanding of the essential parameters controlling the electrical discharge. The present paper reports work carried out without an initiating wire. Work using an initiating wire will be the subject of a further paper.





Photograph A. Plate Bulge test rig

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EXPERIMENTAL ARRANGEMENTS

Electrical Discharge Equipment

The equipment used in this research consists of a high voltage charging unit which charges two 2 μ F low inductance capacitors through a current limiting resistor. At the maximum operating voltage of 40kV, the energy stored in the capacitors is 3,200 joules.

The discharge switch is mounted in series with the underwater spark gap as shown in Figure 2.

There are advantages in using a low pressure gas discharge switch such as speed of switching and reduced energy losses, nevertheless a mechanically operated air gap switch was used as it was cheaper and more simple to use. A spring operated plunger mounted in one of the balls of the ball switch partially bridges the gap when it is released causing a breakdown of the gap which initiates the discharge.

The inductance of the discharge circuit is kept to a minimum of 3 microhenries by keeping the length of single conductors short and by using co-axial low inductance connections where possible.

A calibrated resistive shunt was used to measure the current flowing in the discharge circuit, while voltage was measured using a capacitive divider connected across the terminals of the co-axial cable leading to the spark gap. As a consequence the voltage measured included the voltage drop along the cable. Therefore quantitative measurements were limited to the initial stares of the discharge across the underwater spark gap when the impedance was high. Current and voltage traces were recorded using a polaroid camera with an impulse oscilloscope.





Photograph B

High Voltage Electrical Equipment showing the capacitors, air gap switch and transformer/rectifier unit

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Forming Equipment

Fig. 1 above shows the general arrangement of the forming equipment. It consists of a free forming chamber having a 4" diameter aperture and a lead in radius of 1/4". The seven inch diameter annealed brass blanks were securely clamped round their edges by a clamping ring having grooves cut in its lower surface, corresponding grooves are cut on the body of the chamber, so that drawing-in of the blank during forming is prevented. A vacuum connection is provided to allow the volume under the blank to be evacuated prior to the underwater discharge. The chamber is arranged in a framework with the electrodes positioned at some predetermined distance above the centre of the blank, and the whole assembly is lowered into a tank of water.

Kiyota (10) and others have used the central deflection of the deformed blank as a measure of the work of deformation, although as has been pointed out by Bahrani and Crossland (11), this is open to criticism. Though some specimens were inscribed with a. polar grid by a photo resist technique which enabled a more precise estimate to be made of the work of deformation, this proved to be labourious, and central deflection was used for much of the work described in this paper.



Photograph C. Plate Bulge test rig

Photograph D

High Voltage Electrical Equipment showing the air gap switch transformer/rectifier and control unit



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CHARACTERISTICS OF UNDERWATER DISCHARGES

It is obvious that a knowledge of the characteristics of underwater discharges is important for a complete understanding of the electro-hydraulic forming process. An equivalent electrical circuit for the discharge circuit and spark gap is shown in Fig. 2b in which the total resistance inductance and capacitance are represented by the lumped parameters R, L and C where:

$R = R_C + R_G$

The spark gap resistance R_G decreases with time during a discharge, but if it is assumed constant the circuit becomes equivalent to a simple series R L C circuit which is amenable to a simple analysis and for which the damping will be critical when

$$\varepsilon = \frac{R}{2} \sqrt{\frac{C}{L}}$$

Fig. 3 shows that energy is released most rapidly in the resistive component of the circuit for values of tile damping factor a in the range $\varepsilon = 0.5$ to $\varepsilon = 1$. A high rate of energy release may be expected to give a higher shock pressure and consequently the time constant of the circuit

$$t_c = \sqrt{LC}$$

should also be small. This implies that the inductance L should be kept as low as possible as the capacitance is fixed by energy storage requirements.









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ENERGY LOSSES IN THE PRE-BREAKDOWN PHASE

Preliminary experiments showed that the work of deformation was extremely variable from one discharge to the next. This was attributed to the discharge characteristics. These characteristics have been examined and they will be fully reported elsewhere, however the characteristics which are important for electrohydraulic forming are described below.

When a potential difference is applied across an underwater spark gap, there is a time delay before a spark discharge occurs, as can be seen from the oscillograph traces shown in Fig. 4. Time delays from a few microseconds up to milliseconds have been noted by other workers. (12.13.) In this work, the length of the time delay has been found to be largely controlled by the strength of the local electric field adjacent to the spark gap electrodes, though at low conductivities the conductivity of the discharge medium may also have an effect.

The variation of time delay with the applied voltage across the spark gap at a constant gap is shown in fig. 5. Similar results are obtained for other gap widths. From these tests it has been found that the length of time delay is a function of the average voltage gradient across the spark gap alone. As the voltage gradient across the spark gap decreases, the length of the time delay period increases, until below a certain value, breakdown fails to take place and the charge in the capacitors leaks away by ionic conduction mechanisms in the fluid. Even if the spark gap breaks down there can be appreciable dissipation of energy during the delay period, as is shown in Fig. 6. This energy may be evaluated by measuring the voltage across the capacitors at the start and end of the delay period. The energy lost in the discharge circuit resistance, or stored in the inductance is negligible during this phase.



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PERCENTAGE DISCHARGE ENERGY

It is convenient to define a quantity "Percentage Discharge Energy" (P_E), which is

P_E = <u>Energy stored in the capacitor bank at breakdown x</u> 100 Energy initially stored in the capacitor bank

It must be realised however that not all the energy in the capacitor bank at breakdown is released across the spark gap, as significant energy is dissipated in the conductors and switch.

The loss of energy experienced in the delay period would suggest that the conductivity of the discharge medium may be important and tests were carried out with tap water with varying amounts of sodium sulphate added to increase the conductivity from 73 µmhos/cm up to 850 µmhos/cm. This had no detectable effect on the length of the delay time, but the energy dissipated during the delay period was found to increase quite rapidly as the conductivity was raised. When distilled water was used as a discharge medium breakdown frequently did not occur at gap widths of 5/8" or greater, and even when it did occur it was only after a long and variable delay time. This effect may be due not only to-the low conductivity of distilled water but also because of the relative absence of suspended solid matter in it.



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SURFACE AREA AND PROXIMITY EFFECTS

All the above tests were carried out using an isolated spark gap immersed in water and using conical copper alloy electrodes in which only the tips were exposed to the electrolyte. These electrodes were subjected to repeated discharges before the experiments above were carried out. Different electrode materials such as brass, copper, stainless steel and mild steel were used, but there was no significant effect on the breakdown or discharge characteristics. The area of the electrode tip exposed to the electrolyte was increased and this raised the amount of energy dissipated during the delay period, but a corresponding reduction was not obtained if the exposed electrode area was reduced below approximately that of a 1/2" diameter hemisphere. Changing the shape of the electrode had some effect on the delay time, spherical electrodes gave the longest delay time and conical and plane electrodes gave similar but shorter delay times.

The effect of electron emission by field emission from the cathode has been recognised as playing an important part in the breakdown mechanism in liquids. (14). Field emission is held to occur from asperities on the cathode if the local fields at these asperities are greater than $10^5 - 10^6$ volts/cm, and consequently it would appear probable that a general distortion of the electric field near the electrode could have a significant effect on spark initiation. Such a distortion can be achieved by placing a metal, or similar conducting object close to the electrode. It was in fact found that presence of the forming chamber itself produced a considerable reduction in the delay time. With the chamber in position breakdown was found to occur across a 3" wide gap after a delay period of 5-10 microseconds, whereas in its absence, breakdown would not occur with gap widths in excess of $1\frac{7}{6}$ ". The variation of percentage discharge energy with gap width, with and without the forming chamber in position is shown in Fig. 7.





Photograph F Electro-hydraulically formed stainless steel denture in the forming mould.

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DELAY PERIOD AND PERCENTAGE DISCHARGE ENERGY

The experiments have demonstrated the great importance of the delay period on the percentage discharge energy, and the even more significant effect of the distortion of the field round the electrodes caused by the proximity of a metal object, such as the forming chamber. However, the loss of energy during the delay period will not be seriously affected by the capacitance of the storage condensers, so this loss will form a smaller percentage of the stored energy as the capacitance is increased.

The formation of spark channels and the characteristics of underwater discharges have been examined by various authors. (15, 16,17). As soon as a low impedance spark channel has been formed, the electrical energy remaining in the capacitors is rapidly dissipated, and the resulting sudden rise in pressure in the spark channel generates shock waves which radiate from the channel.

The hot gases created continue to expand to form a gas bubble which reaches a maximum size and then contracts and expands cyclically for several cycles before venting to atmosphere. Similar behaviour has been noted with high explosives detonated underwater.





Photographs G and H Etched Metallurgical specimens of annealed (top) and explosively formed brass specimens. The structure of the formed plate shows characteristics of explosively formed specimens.

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FORMING EXPERIMENTS

From the previous section it would seem probable that the energy dissipated in the slow discharge during the delay period contributed nothing to the work of deformation. This would appear to be confirmed by tests in which the deformation was measured with all the parameters kept constant, except the duration of the delay period. Advantage was taken of its random nature to examine the effect of the delay period, and the results are shown in Fig. 8. It proved impossible to obtain results with percentage discharge energies lower than 30%, and the linear relationship shown can only be assumed. It will be seen, however, that the use of this as a correction has a significant effect in reducing the scatter previously apparent in the results.

The effect of varying the gap width keeping the other controllable parameters constant is shown in Fig. 9. Fig. 10 shows the same curve with the results connected to 100% discharge energy. There appears to be an optimum in the curve at a gap width of 1.75" and it is perhaps significant that at this particular gap width and voltage (Fig. 11) the circuit is critically damped. It should be noted, however, that at large gap widths, the gap width becomes comparable with the diameter of the deformed portion of the specimen, and this may have some effect on the results.



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FORMING PARAMETERS

The effect of varying the stand off distance with the depth of immersion of the spark gap kept constant was investigated. From Fig. 12 it will be seen that over most of the range there is a linear relationship between the inverse of central deflection and the standoff distance. If the results are corrected to 100% discharge energy, the slope of the straight line portion of the curve is reduced. This is a consequence of the increased delay period at increased standoff caused by a reduction of the influence of the proximity of the forming chamber to the electrodes. At very small standoff distances, the central deflection is apparently independent of the magnitude of the stand-off, but in this region the effects due to the cylindrical nature of the discharge become increasingly apparent.



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During these tests, discharges to the forming chamber and specimen, which had frequently proved troublesome, were eliminated by covering the specimen with a thin self-adhesive polythene sheet, and by insulating the forming chamber from earth. Fig. 13 shows a photograph of typical samples of formed plates. At small gap widths, the deformed plates are portions of a spherical shell, and the discharge is very underdamped. At larger gap widths the deformed plates are much more conical in shape, and this is normally attributed to a sharper pressure pulse under these conditions. Similar results are found with explosive forming. Specimens on which a grid has been marked, as in Fig. 14 allow amore detailed examination of the hoop and thickness strain distributions. Fig. 15 shows the variation of these strains for one of the specimens. It is also possible with such specimens to estimate the work of plastic deformation and consequently the overall conversion of electrical energy into plastic work. This was found to be 12% under optimum conditions. If this conversion had been based on energy transmitted through the solid angle subtended by the blank, assuming a point discharge, then the efficiency is 40%.





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CONCLUSIONS

This investigation has demonstrated the importance of the energy lost in the delay period with an open gap underwater spark discharge. It is believed that the disagreement between the results of previous investigators can be largely attributed to a lack of recognition of the role of energy lost in the delay period.

The understanding of the influence of various parameters on the delay period should enable more consistent results to be achieved in electro-hydraulic forming. It is possible with the correct design of the electrode system that the delay period and the energy dissipated during the delay period can be reduced to give high values of the percentage discharge energy under most conditions.

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