$$(\tfrac{1}{2}CV^2)^{0.363} = 339\,\frac{\Delta T}{r}\,R^{0.882}\left(\frac{\sigma\rho}{g}\right)^{1/2} \tag{10}$$

where

Δ = deflection, in.
T = thickness, in.
r = radius, in.
R = standoff, in.
σ = strength, psi
ρ = density, pci
g = 386 in/sec^2
$(\tfrac{1}{2}CV^2)$ = energy required to achieve the given deformation, joules

There still exists some question as to whether this energy should be obtained at high voltage and low capacitance or at moderate voltage and high capacitance. A set of experiments was carried out wherein the voltage and capacitance were varied from test to test while the total energy of the discharge remained constant. The results are shown in Fig. 14 where deflection is plotted against capacitance for two values of constant energy. Examination of these data shows that for the range of values investigated in the present work it makes little difference whether high voltage or high capacitance is used.

The operation of deforming a diaphragm gauge (which is almost entirely thinout), should require more force than a drawing operation of comparable depth, depending on the constraint forces which act on the flange of the workpiece during the drawing operation. Therefore, it should be recommended that for any specific drawing operation a factor should be determined to correct equation (10) for the operation of interest. Once this factor is applied, the revised equation may be used to extrapolate subscale test results or to estimate the effects of changing materials or any other major variable for the specific forming operation of interest. It should be borne in mind that all of the foregoing experimental results were obtained at a rather low range of energy values, and that they have not yet been verified for high-energy levels. Therefore large extrapolation of the present results should be made with caution.

Conclusions

1 The distance between the spark and the water surface is unimportant beyond a certain depth.

2 No effect was found in varying initiating wire material.

3 Forming efficiency increases as initiating wire diameter decreases.

4 Forming efficiency increases as spark gap increases within the range investigated.

5 The expression derived herein may be used to estimate the effects of changing major variables of the process or to extrapolate subscale test data.

Acknowledgment

The author would like to thank Dr. M. E. Merchant, Director of Physical Research under whose supervision this work was done. Also, acknowledged is the helpful discussion by Mr. Serope Kalpakcioglu and the fine work of Mr. Robert V. Popplewell in performing the experimental research reported herein.

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DISCUSSION

G. Pfanner[2]

I consider the paper to be a very successful attempt to formulate a working theory to predict the formed dome depth of sheet-metal parts based on material properties and process variables. Mr. Kegg's experimental results have confirmed the validity of the formula for the energy levels and deformation depths which he has investigated. However, since the discharge level employed was so low (below 3300 joules) and the formed depths were so shallow (below 0.7 in.), I agree that "large extrapolation . . . . . should be made with caution." For example, strain-hardening increases exponentially with dome depths and may, therefore, not be negligible (see equation (8)) for deeper domes.

Our experimental results with 10,000 to 150,000 joule discharges confirm conclusions 1, 2, and 4. With regard to 3, an optimum wire diameter was found to exist for all wire materials investigated. See Fig. 15, p. 133, which was obtained with 12,000 joule discharges. This is in disagreement with Fig. 4 of the paper.

With regard to Fig. 5, I have enclosed a graph, Fig. 16, p. 133, which suggests that deformation would finally fall off with longer gap length.

Fig. 7 appears to be a reasonable result. However, we generally find the slope to be very low. It would be of interest to establish whether this difference lies in the proportion of discharge energy to blank strength or to the air bubble technique or both.

As a minor matter, equation (2) can be obtained by integration of equation (1) over all time so that $s = \alpha\theta$, $a = m$, and $b = n$, which is a reduction in constants.

The statement of the force unbalance in equation (5) in terms of shear leads to a simple solution. Actually, the more complex condition of forming rather than shearing generally occurs. The reason for denoting $\sigma/2$ as shear stress and defining σ as a tensile stress is not understood.

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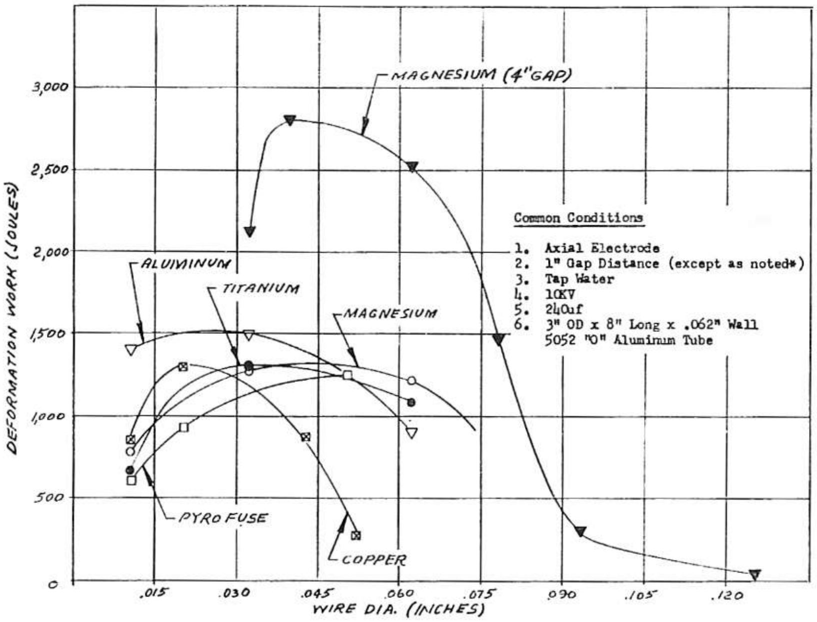

Fig. 15 Effect of wire diameter on deformation work for several wire materials

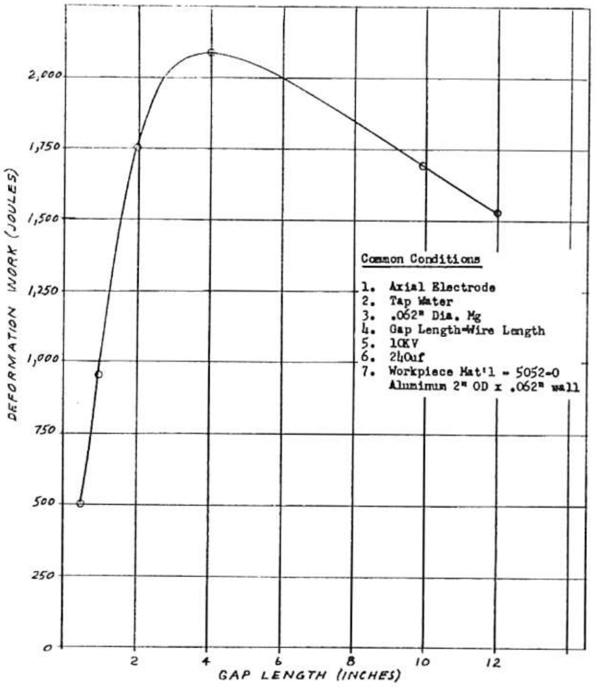

Fig. 16 Effect of gap length on deformation work

Author's Closure

I would like to thank Mr. Pfanner for his discussion. It is interesting to learn how results obtained at low discharge energies compare to results obtained at the higher energies with which he has experience. It should be pointed out that Figs. 15 and 16 with deformation work as ordinate may be compared to the earlier figures with central deformation as ordinate by rearranging equation (8).

$$\Delta = A v_m$$

$$\Delta^2 = A^2 v_m^2 = \frac{1}{A_1}(\mathrm{KE})_m$$

where

$$A = r\left(\frac{\sigma g}{\rho}\right)^{-1/2}$$

$$A_1 = \frac{m}{2A^2}$$

$(\mathrm{KE})_m$ = maximum workpiece kinetic energy

Now if kinetic energy is nearly all converted to deformation work, we have approximately:

Deformation Work $= A_1\Delta^2$

Thus the ordinate of the last two figures is proportional to the square of the ordinate of earlier figures.

As Mr. Pfanner points out, the arguments leading to equation (5) and its approximate solution, equation (7), are not too clear. This series of steps may be summarized as follows:

1 The path taken by a system of particles or, in the limit, a continuous medium (in this case the shape of the gauge during deformation) will be such that the work done by external forces will be a minimum.

2 Thus if we choose a shape or mode of deformation which we know from experience the gauge will not take, we have a situation guaranteed to require greater forces than the actual case.

3 If we show that the deformation forces for this model (which are greater than the actual deformation forces) are negligible compared to inertia forces during the accelerative period of gauge motion, then we may ignore plastic deformation during this period.

4 As a result of these arguments we obtain an equation of motion which is easily integrated to give the velocity and kinetic energy of the workpiece at the end of this period.

5 The use of one half the yield stress in tension as the yield stress in shear is in accordance with the maximum shear stress criterion of flow. If the energy of distortion criterion is a better description of the behavior of any particular material, then this procedure may be in error by as much as 15 percent.