Def Sci J, Vol 34, No 3, July 1984, pp 235-256

Explosive Forming of Low Carbon Steel Sheet into a Stepped Disc Shape

S. Balasubramaniam, S. Sarvat Ali, E. S. Bhagiradha Rao
Defence Metallurgical Research Laboratory, Hyderabad-500258

Received 13 December 1983

Abstract. This paper deals with the explosive forming of deep drawing quality steel into a two stepped disc type shape. An attempt has been made to predict the forming parameters from theoretical considerations by equating the disc shape with an equivalent dome. Results of forming this shape in a single-stage *vis-a-vis* forming in two-stages are compared.

1. Introduction

The development of Hot Isostatic Pressing (HIP) technology for the production of jet engine turbine discs is being carried out at our laboratory. This requires turbine disc shaped capsules out of sheet metal. The conventional techniques such as spinning or deep drawing are proving to be expensive as the quantities to be produced are limited. So, explosive forming has been chosen as an alternative technique to form the capsules. A programme has been initiated to obtain by explosive forming a simplified configuration out of 2 mm thick low carbon steel sheet as shown in Fig. 1. The paper deals with deriving the explosive forming parameters from the theoretical consideration and matching them with actual field trials on this component.

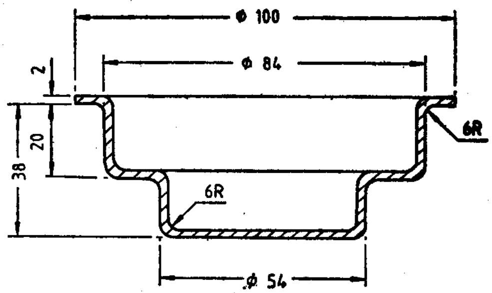


Figure 1. Simplified turbine disc configuration for explosive forming.

2. Theoretical Parameters

2.1 *Equivalent Dome*

The explosive forming method selected is a stand-off operation by under-water explosion as shown schematically in Fig. 2, water being more effective than air[1] as a pressure transmitting medium. Plastic explosive PEK – 1 (which is mainly 85% tetryl with additives of rubber, oil and plasticizer), with a specific energy[2] of 406 Mkg per gm is chosen for this work, as it is readily available and found to be convenient to

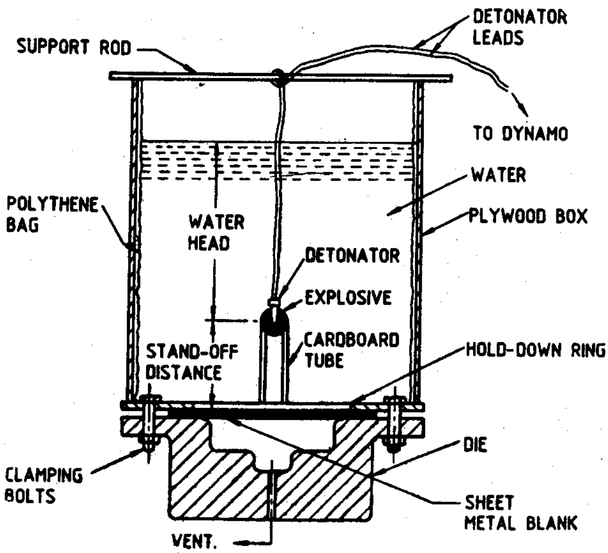
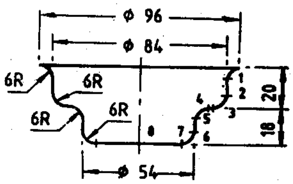


Figure 2. Schematic of underwater explosive forming set-up.

work with. The two basic parameters to be known beforehand for explosive forming are the stand-off distance and the explosive charge weight. Literature does not show any comprehensive formulae that can be readily and precisely applied for any given shape and material. However, a good deal of published work has formalised a fair theoretical basis for forming dished-end type, round domes[3,4]. An attempt has been made here to obtain the optimised estimate of charge weight and the stand-off distance for the component of our interest, by considering the theoretical parameters for forming a hypothetical dome whose surface area will equal the surface area of the component.

We assume that the depth of the equivalent dome is the maximum depth of the component, namely 38 mm. Equating the surface area of the component (Table 1 a) with the surface area of the equivalent dome, which is taken to be a segment of a sphere, we get

Table 1 (a). Surface Area calculation;.



1. $\frac{2\pi 6}{4} \times \pi 96 = 2842.4$
2. $\pi 84 \times 8 = 2111.2$
3. $\frac{2\pi 6}{4} \times \pi 72 = 2131.8$
4. $\frac{\pi (72^2 - 66^2)}{4} = 650.3$
5. $\frac{2\pi 6}{4} \times 66 = 1954.2$
6. $\pi 54 \times 6 = 1017.8$
7. $\frac{2\pi 6}{4} \times \pi 42 = 1243.6$
8. $\frac{\pi 42^2}{4} = 1385.4$

TOTAL SURFACE AREA = 13336.7 OR 13337 mm^2

(a)

$$\pi \left(\frac{D^2}{4} + 38^2\right) = 13337$$

Therefore

$$D = 106 \text{ mm}$$

However, the maximum depth of a spherical dome that can be formed without catastrophic thinning is limited by the onset of necking during plastic deformation of the sheet forming operation, and is given by[5] the following relation

$$H_{max} = \frac{D}{11}(2n + 1)(4n + 13) \qquad (1)$$

Where

H_{max} = Maximum permissible depth of draw

D = Diameter of the dome, which, in our case is 106 mm

n = Strain-hardening coefficient in the plastic stress-strain relationship of $\sigma = k\epsilon^n$ where $n = 0.261$ and $K = 54.22$ for deep drawing steel[6]

H_{max} = 44.6 mm

Therefore, the assumed depth of 38 mm of the equivalent dome is within the 'necking limit'.

2.2 *Efficiency of Explosive Forming*

It is only a portion of the chemical energy released by the explosive charge that is utilised in the deformation of the sheet blank into the die cavity. The energy transfer medium and the stand-off distance, among other factors are known to affect the efficiency of this energy transfer which can be taken to mean the efficiency of the forming operation. Literature[7,8,9&10] cites different values for this efficiency, varying from 0.11 to 0.5. It is therefore desirable to determine the efficiency of energy transfer in our set-up and experimental condition.

The efficiency of the energy transfer and the configurational efficiency due to stand-off nature of the operation find place in the energy balance method used by Ezra[11] which equates U_T, the total strain energy of deformation with E_T, the amount of explosive energy that will be utilised for the deformation at a given stand-off.

According to Ezra,

$$E_T = \tfrac{1}{2}\,\eta\,(1 - \cos\phi)\,W e \qquad (2)$$

and

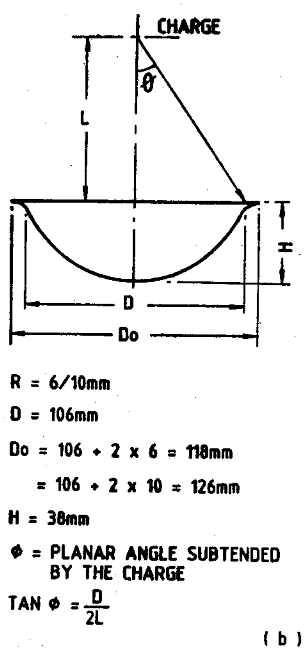
$$U_T = U_D + U_F$$

where

η = Efficiency of the energy transfer from the explosive to the blank through the medium

ϕ = Planar angle subtended at the centre of the charge by the die-opening diameter (Table 1b)

Table 1 (b). Equivalent dome.



W = Charge weight in grams

e = Specific energy of the explosive in M kg/gm

U_D = Strain energy for deformation into die cavity (Eqn. 5)

U_F = Strain energy for flange pull-in across the die corner radius (Eqn. 6)

Thus

$$U_T = \tfrac{1}{2}\,\eta\,(1 - \cos\phi)\,W\,e \tag{3}$$

Therefore

$$\eta = \frac{U_T}{\tfrac{1}{2}(1 - \cos\phi)\,W\,e} \tag{4}$$

In order to determine U_D and U_F for computing U_T values for Eqn. (4), the following formulae[12] are made use of.

For a strain hardening material

$$U_D = \frac{\pi}{4} D^2 t_0 \frac{K}{n+1}\left[Ln\left\{1 + 4\left(\frac{H}{D}\right)^2\right\}\right]^{n+1} \tag{5}$$

Where

D = Diameter of the dome to be formed

H = Depth of the dome to be formed

t_0 = Blank thickness

k, n = Constants in the plastic stress-strain relationship, $\sigma = K\epsilon^n$

Similarly

$$U_F = \pi\left(\frac{\sqrt{3}}{3}\right)^{n+1} \frac{K}{n(n+1)}\, t_0 \left[\left(\frac{B_0 - B}{2}\right) B_0\right]^{n+1} \left[\left(\frac{D_0}{2}\right)^{-2n} - \left(\frac{B_0}{2}\right)^{-2n}\right] \tag{6}$$

Where

B_0 = Blank diameter before forming,

B = Blank diameter after forming,

D_0 = $D + 2r_e$, where r_e is the die entry radius.

$(B_0 - B)$ can be determined from the empirical graph[13] between normalised pull-in $\left(\frac{B_0 - B}{D}\right)$ and normalised depth of draw $\left(\frac{H}{D}\right)$ for values of $\frac{B_0}{D} = 1.4, 1.5$ & 1.6 (Fig. 3). In our analysis, we have assumed a value of $\frac{B_0}{D} = 1.4$

Using a somewhat similar approach, Noble & Oxley[9] have related the work done in deformation with the explosive energy of a given charge weight and given stand-off through the expression;

$$t_0 Y \pi H^2 = W e \eta \frac{\theta^2}{4} \tag{7}$$

Where

t_0 = Thickness of the blank,

Y = Yield stress of the material,

W = Charge weight,

η = Efficiency of the energy transfer from the explosive to the blank,

2θ = Solid angle subtended by the blank at the charge.

This gives

$$\eta = 4\pi \frac{H^2}{W e \theta^2 / t_0 Y} \tag{8}$$

2.3 *Charge Weight and Stand-off Distance*

With a known value of η, Eqn. (3) or Eqn. (7) can be applied to determine the charge weight, provided the stand-off distance required for forming the component is fixed arbitrarily. There appears to be no relationship that would enable us to calculate the stand-off distance, without the prior knowledge of the charge weight, or vice versa.

An attempt has been made to get over this difficulty by dividing Eqn. (3) with Eqn. (7) to eliminate W, the charge weight.

Thus

$$\frac{U_T}{t_0 Y \pi H^2} = \frac{\frac{1}{2} \eta (1 - \cos \phi) We}{We \eta \theta^2 / 4}$$

Since 2θ, the solid angle, is geometrically related to the planar angle ϕ through the relation

$$2\theta = 2\pi (1 - \cos \phi) \tag{9}$$

We then obtain,

$$\frac{2}{\pi (1 - \cos \phi)} = \frac{U_T}{t_0 Y H^2}$$

or

$$\cos \phi = 1 - \frac{2 t_0 Y H^2}{\pi U_T} \tag{10}$$

Eqn. 10 will enable us to calculate ϕ from known values of t_0, Y, H & U_T.

From Table (1b), it can be seen that

$$\tan \phi = \frac{D/2}{L} \text{ or } \frac{L}{D} = \frac{1}{2 \tan \phi}$$

Which, from Eqn. (10), may be rewritten as

$$\frac{L}{D} = \frac{1}{2 \tan \left[\cos^{-1} \left(1 - \frac{2 t_0 Y H^2}{\pi U_T} \right) \right]} \quad (11)$$

Since the component to be formed has been converted into an equivalent dome, the dimensions of this dome and the corresponding calculation of U_T alongwith the known characteristics of the material can now be used in Eqn. (10) and Eqn. (11) to arrive at a plausible L/D for the actual trials. Two different values of L/D can arise, in our study here, corresponding to two different values of U_T, one arising from assuming a die entry radius of 6 mm as prescribed in the component drawing (Fig. 1), and another arising from a more generous die entry radius of 10 mm which, being less sharp in its curvature, is arbitrarily considered as an alternative choice in the event of failure of 6 mm radius forming. With the knowledge of L/D & η, the charge weight for the component can be computed from Eqn. (3) or Eqn. (7), by means of the equivalent dome.

3. Experimental Results

3.1 *Determination of Efficiency*

Blanks of 150 mm average diameter were cut from 2 mm thick 'deep drawing' quality steel sheet conforming to *B. S.* 1449 : *En 2A*. Specimens of the steel were tested for mechanical properties and the average yield strength was found to be 22 kg/mm². An 'open-well' die of 84 mm die-opening was machined from a large mild steel round. The die entry radius was maintained at 10 mm. The water medium was contained in disposable plywood boxes lined inside with polythene sheet. A water-head of around three times the stand-off distance was used. A vent hole was provided at the centre of the die. The blank and the die were greased to minimize friction effects. Evacuation of the die, although provided for, has not been done in these investigations.

Sixteen experiments of forming trials were conducted with arbitrarily chosen charge weights and stand-off distances and the resulting dome depths in the blanks were measured as detailed in Table 2.

Both Eqns. (4) and (8) have been applied to the above experiments to obtain a comparison of efficiency. The calculations, tabulated in Tables 3 and 4, show that

Table 2. Explosive forming trials with varied charge weights and stand-off distances

Blank Diameter (B_0)	Dia of Blank after forming (B)	Charge weight (gms)	Stand-off Distance (mm)	Formed Depth (mm)
150	145	10.5	47	34
150	146	5	47	28.5
151	147	10	80	30
150	145	13	94	32.7
152	149	5	80	21
152	149	8	113	23.5
152	151	8	141	13
152	151	10	170	12
144	143	12	170	13.3
147	146	18	188	13.5
152	150	23	188	15.2
152	150	28	188	19.9
152	150	13	141	18
152	150	20	150	22
152	150	23	170	18
152	150	30	170	21.3

Table 3. Trials for computation of efficiency of energy transfer based on Ezra's method

W (gms)	L Stand-off Distance (mm)	$\frac{L}{D}$ $D=104$mm	$(1-\cos\phi)$	U_D (Mkg)	U_F (Mkg)	U_T U_D+U_{OF} (Mkg)	$\frac{1}{2}(1-\cos\phi)We$ ($e=406$ Mkg/gm) (Mkg)
10.5	47	0.45	0.331	198.6	20.3	218.9	705.5
5	47	0.45	0.331	135.4	15.3	150.7	335.9
10	80	0.77	0.162	151.6	15.7	167.3	328.8
13	94	0.90	0.126	182.8	20.3	203.1	332.5
5	80	0.77	0.162	67.4	11.2	78.6	164.4
8	113	1.1	0.089	87.5	11.2	98.7	144.5
8	141	1.36	0.062	21.3	2.8	24.1	100.7
10	170	1.63	0.044	17.5	2.8	20.3	89.3
12	170	1.63	0.044	22.5	2.3	24.8	107.2
18	188	1.81	0.036	23.4	2.5	25.9	131.5
23	188	1.81	0.036	31.2	6.7	37.9	168.1
28	188	1.81	0.036	59.4	6.7	66.1	204.1
13	141	1.36	0.062	46.8	6.7	53.5	163.6
20	150	1.44	0.056	75.1	6.7	81.8	227.4
23	170	1.63	0.044	46.8	6.7	53.5	205.4
30	170	1.63	0.044	69.7	6.7	76.4	267.9

$$\eta = \frac{\Sigma U_T}{\Sigma \frac{1}{2}(1-\cos\phi)We}, \quad \Sigma U_T = 1381.6, \ \Sigma \frac{1}{2}(1-\cos\phi)$$

$We = 3677.3$ and $\eta = 0.38$ (approx.

Table 4. Trials for computation of efficiency of energy transfer based on Noble & Oxley's method

W (gm)	L Stand-off Distance (mm)	$\frac{L}{D}$ (D=104mm)	2θ	θ^2	H (mm)	H^2	$\frac{We\theta^2}{t_0Y} \times 1000$ (mm kg)
10.5	47	0.45	2.08	1.08	34	1156	104637.3
5	47	0.45	2.08	1.08	28.5	812.3	49827.3
10	80	0.77	1.012	0.256	30	900	23621.8
13	94	0.90	0.792	0.157	32.7	1069.3	18832.8
5	80	0.77	1.012	0.256	21	441	11810.9
8	113	1.1	0.566	0.08	23.5	552.3	5905.5
8	141	1.36	0.39	0.038	13	169	2805.1
10	170	1.63	0.276	0.019	12	144	1753.2
12	170	1.63	0.276	0.019	13.3	176.9	2103.8
18	188	1.81	0.226	0.0128	13.5	182.3	2125.9
33	188	1.81	0.226	0.0128	15.2	231	2716.5
28	188	1.81	0.226	0.0128	19.9	396	3307.1
13	141	1.36	0.39	0.038	18	324	4558.3
20	150	1.44	0.346	0.03	22	484	5536.4
23	170	1.63	0.276	0.019	18	324	4032.3
34	170	1.63	0.276	0.019	21.3	453.7	5259.5

$$\eta = 4\pi \frac{\Sigma H^2}{\Sigma \frac{We\,\theta^2}{t_0Y} \times 1000}, \quad \Sigma H^2 = 7815.8, \quad \Sigma \frac{We\,\theta^2}{t_0Y} \times 1000 = 24883.7,$$

$$\eta = 0.40 \text{ (approx.)}$$

both Ezra's Eqn. (4) as well as Noble & Oxley's Eqn. (8) yield approximately identical values of this efficiency: 0.38 and 0.40 respectively. The mean values of these two, 0.39, is assumed to be the efficiency for the conditions of our set up, which is almost the same as reported by Noble & Oxley[19].

3.2 *Determination of L/D*

The total strain energy for forming the equivalent dome can now be determined from Eqn. (5) in the following manner:

Since

$\frac{B_0}{D}$ is assumed to be 1.4,

$$B_0 = 148.4 \text{ mm for } D = 106 \text{ mm}$$

$$D_0 = D + 2r_e$$

$$= 106 + 12 = 118 \text{ mm} \quad - \text{ for } r_e = 6 \text{ mm}$$

and

$$D_0 = 106 + 20 = 126 \text{ mm} - \text{for } r_e = 10 \text{ mm}$$

For

$$\frac{H}{D} = \frac{38}{106} = 0.36, \text{ the graph at Fig. 3 by extrapolation gives}$$

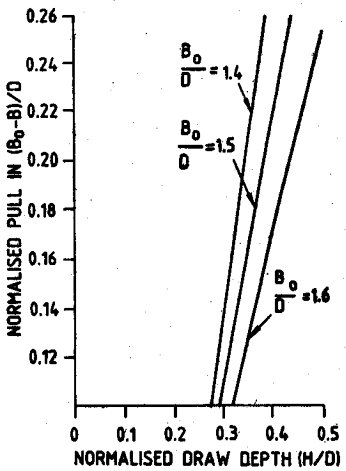


Figure 3. Parametric curves for blank-pull-in-vs draw depth

$$B_0 - B = 25.4$$

Using other known values

$$U_D = 250.2 \text{ Mkg}$$

From Eqn. (6),

$$U_F = 94.5 \text{ Mkg for 6 mm die corner radii,}$$

$$= 66.5 \text{ Mkg for 10 mm die corner radii}$$

The total strain energy for the equivalent dome

$$U_T = U_D + U_F = 344.7 \text{ Mkg for 6 mm die corner radii}$$

$$= 316.7 \text{ Mkg for 10 mm die corner radii}$$

Applying these values of U_T in Eqn. (11)

$$\frac{L}{D} = 0.94 \text{ for 6 mm die corner radii,}$$

$$\frac{L}{D} = 0.89 \text{ for 10 mm die corner radii.}$$

3.3 *Single Stage Forming*

Two mild steel dies were made conforming to the component shape of Fig. 2, one with corner radii machined to 6 mm (referred to hereafter as 6 mm die), and another with corner radii of 10 mm die. The overall die dimensions are as in Fig. 4. Using the equivalent dome dimensions Eqns. (3), (7) and (11) have been applied to calculate the charge weight W, and stand-off distance ratio L/D for forming the component in a single shot. These calculations are presented in Table 5, wherein Table 5a shows the parameters obtained for 6 mm die and in Table 5b the parameters for 10 mm die.

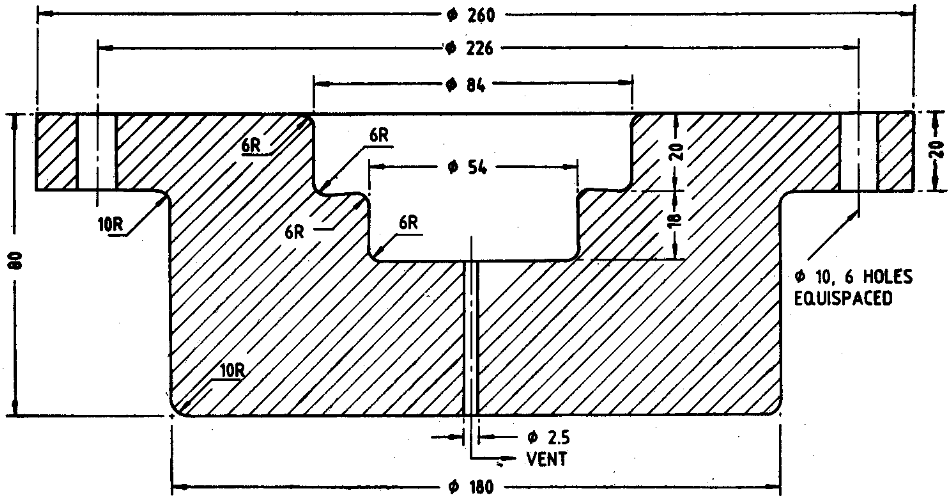


Figure 4. Explosive forming die in mild steel.

Table 5 Charge weights and stand-off distance for single-stage forming of the component based on the equivalent dome.

Table 5a 6 mm corner radii die

U_D From Eqn. 5 (Mkg)	U_F From Eqn. 6 (Mkg)	U_T (Mkg)	$t_0 Y \pi H^2$ (C.M. Kg)	$(1-\text{Cos}\,\phi)$ From Eqn. 10	2θ From Eqn. 9	θ^2	η	W Based on Eqn.3 (gms)	W Based on Eqn.7 (gms)	W Rounded off (gms)	L/D From Eqn. 11	L Stand-off distance for the die opening of 96mm (84+12) (mm)
250.2	94.5	344.7	199.6	0.117	0.735	0.135	0.39	37.2	37.4	37	0.94	90

Table 5b 10 mm corner radii die

												Die opening D of 104 mm (84+20) mm
250.2	66.5	316.7	199.6	0.128	0.804	0.162	0.39	31.3	31.2	31	0.89	93

The stand-off distance L to be used for the field trials is derived from the appropriate L/D ratio and the appropriate die opening diameter which in the case of 6 mm die is 96 mm, and in the case of 10 mm die is 104 mm. In order to evaluate the components formed from parameters of Table 5a, a few other arbitrary combinations of charge weight and stand-off distance, higher and lower than the calculated parameters, have been selected for further trials as shown in Table 6.

Table 6. Results of trials on 6 mm corner radii die for single stage forming

Trial No.	W Charge Weight (gm)	L Stand-off Distance (mm)	Result of Forming
EF 1	37	90	Both steps formed with partial fracture at 84 dia and small fracture at the bottom.
EF 2	34	90	Both steps formed with 30 dia semi-circular fracture at the bottom.
EF 3	40	90	Both steps formed with 32 dia circular fracture at the bottom.
EF 4	37	80	84 dia formed and 54 dia sheared off
EF 5	37	110	Both steps formed with big triangular fracture at the bottom.

The results of the trials on 6 mm die are presented in Table 6 and Fig. 5 and the results of the trials on 10 mm die are shown in Table 7 and Fig. 6. All the trials on 6 mm die have resulted in cracking in the bottom surface of the component; it is also seen that all the components have some taper in the two vertical faces of the component. From the taper analysis shown in Table 12, it can be noticed that the least taper with least fracture belongs to trial EF 1 which has the calculated parameters of 37 gm charge weight and 90 mm stand-off distance.

If the failure of bottom cracking is mainly on account of the sharpness of die corner radii, which is known to be a factor in causing excessively localized thinning leading to fracture, then the use of increased radii in conjunction with corresponding forming parameters should result in a totally crack-free formation. This is borne out by the crack-free forming result of trial EF6 (Table 7 and Fig. 6) obtained with

Table 7. Result of trial on 10 mm corner radii die for single stage forming

Trial No.	Charge Weight (gm)	Stand-of Distance (mm)	Result of Forming
EF 6	31	93	Both steps formed perfectly

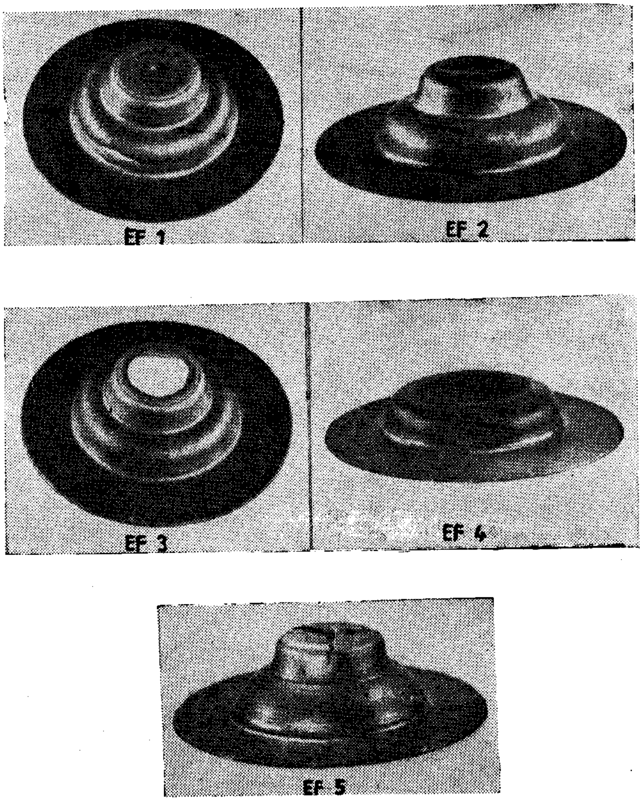


Figure 5. **Components-single stage formed on 6 mm die**

Figure 6. **Components-single stage formed on 10 mm die**

10 mm die and charge parameters of Table 5b. Although the use of arbitrarily increased 10 mm radii has also resulted (EF6) in an overall decrease in taper of the vertical faces as compared to the taper of the trial EF1 with 6 mm die (Table 12), the observed average taper of 7.5° in EF 6 still calls for further improvement.

3.4 *Two Stage Forming Trials*

In order to overcome both the bottom cracking problem in forming the 6 mm corner radius component and the taper problem persisting in 6 mm and the 10 mm corner radius component, it was proposed to form the shape in two stages, first to a dome and then to the final component with 6 mm corner radii. The size of the dome for the first stage operation has been geometrically determined (Fig. 7) on the basis of a segment of a sphere that will touch the steps inside at 84 mm diameter and at 54 mm diameter. The diameter of this dome remains the same as that of the component, namely, 84 mm and maximum depth at central point works out to 34.5 mm (which, it may be noted, is within the maximum permissible limit of 43.8mm as given by Eqn. (2)).

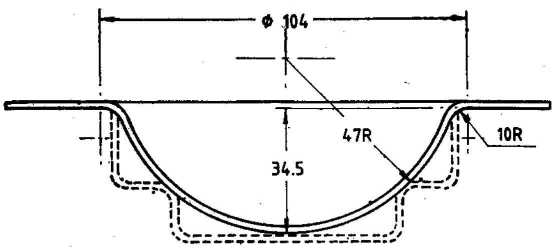


Figure 7. Derivation of dome shape for first stage (dotted line shows final component).

A mild steel die for the first stage dome with these dimensions has been fabricated, with a die entry radius of 10 mm. Based on calculations similar to the single-stage shown previously, the charge weight and stand-off distance have been determined (Table 8). Since the charge weight from Eqn. (3) and Eqn. (7) are found to be

Table 8. Charge weight and stand-off distance for the first stage dome

U_D From Eqn. 5 (Mkg)	U_F From Eqn. 6 (Mkg)	U_T (Mkg)	$T_0 y \pi H^2$ (Mkg)	$(1-\text{Cos}\,\phi)$ From Eqn. 10	2θ From Eqn. 9	θ^2	η	W Based on Eqn.3 (gms)	W Based on Eqn.7 (gms)	W Rounded off Charge Weight (gms)	L/D From Eqn.11	L Stand-off Distance for the Die opening Dia 104mm (mm)
206.7	37.2	243.9	164.5	0.128	0.804	0.162	0.39	24.1	25.5	25	0.89	93

nearly the same, the rounded off value of 25 gm is chosen for the first stage trial with a stand-off of 93 mm, the result of which (Table 9) shows that these parameters have given a dome conforming closely with the die (Fig. 8). To facilitate second-stage forming, the first stage dome which is in a strain-hardened condition has been annealed at 950°C for two hours.

Table 9 Result of Trial for the first stage dome

Trial No.	Charge Weight (gms)	Stand-off Distance (mm)	Result of Forming
EF 7	25	93	Dome formed perfectly

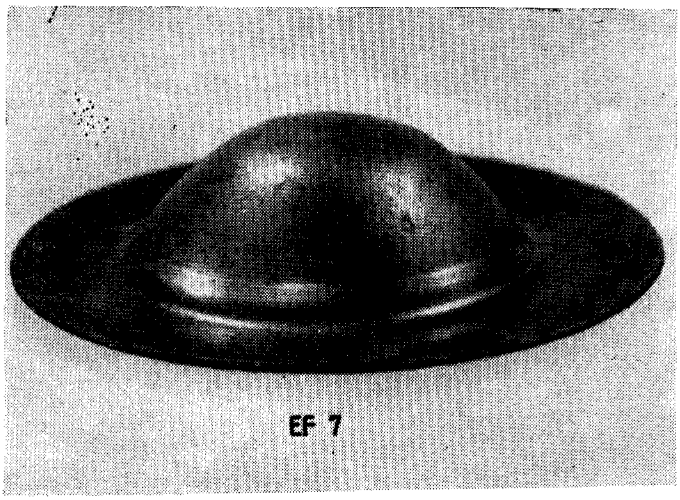


Figure 8. Dome-first stage formed.

To arrive at the forming parameters for the second stage, firstly from Eqn. (3), we can consider the strain energy of the second stage to be the difference between U_T, the strain energy of the component based on equivalent dome calculations and, U_T, the strain energy of the first stage dome.

U_T (Second stage) = U_T (Component)-U_T (First stage)

Applying Eqn. (10) to the second stage to obtain $(1 - \cos \phi)$

$$\cos \phi = 1 - \frac{2\, t_0 Y}{\pi\, U_{T\,(Second\ Stage)}} \left(H^2_{(Component)} - H^2_{(First\ Stage)} \right)$$

In the same manner, Eqn. (7) may be used by equating the difference of $t_0 Y \pi H^2$ (work done for the component) and $t_0 Y \pi H^2$ (work done for the first stage) to the effective explosive energy.

Thus, applying Eqn. (7) i.e.

$$t_0 Y \pi\ H^2_{(Second\ Stage)} = t_0 Y \pi\ H^2_{(Component)} - t_0 Y \pi\ H^2_{(First\ Stage)}$$

The charge weight calculations are tabulated in Table 10 which shows that both Eqn. (3) and Eqn. (7) predict 18 gms for second stage forming.

The stand-off distance ratio, L/D can now be obtained from Eqn. (11). As shown in Table 10, L/D for second stage works out to 1.26. D for second stage is the die opening diameter of the second stage, namely, 96 mm (84+12) and 'L' should be 121 mm. However, since the second stage forming is to be done from the first stage which is 34.5 mm deep at centre, the effective stand-off distance should be $121 - 34.5 \approx 87$ mm.

In order to have a comparative evaluation, an additional trial consisting of 19 gm with 87 mm stand-off was also chosen for the second stage forming.

5. Thinning

Certain amount of thinning (thickness reduction) is inevitable on account of several factors such as blank hold-down pressure, friction, die corner radii etc. While the Ezra's formulae, that have been used have assumed uniform thinning throughout the dome, the actual thinning observed is non-uniform, the maximum occuring near the bottom of the component. Percentage thinning with respect to blank thickness, at identical location in the bottom of the component. for 6 mm die single stage forming, 10 mm die single stage forming, first stage dome forming and second stage forming are presented in Table 13.

The location of the thinning measurements, which is same for all the components studied, is so chosen as to be well away from the cracked regions in the case of cracked components (Viz trials EF 1, EF 2, EF 3 and EF 5).

6. Discussion

The results of explosive forming trials bring out the validity of the use of the concept of an 'equivalent dome' (equivalent in terms of component surface area and a dome depth limited to component depth) in predicting the forming parameters for the component shape in Fig. 1 and its extension to other shapes is also expected to have similar validity. Two formulae have been applied throughout our study. Equation (3) of Ezra is based on the strain energy of deformation as a sum of the energy of deformation to form a dome plus the energy involved in the inevitable flange 'pull-in' arising out of the difference in surface areas between the flat plane of the die opening and the curved dome surface; Ezra's formula also takes into account the strain hardening effect that is inherent in explosive forming. On the other hand, the

Table 10. Charge weight and stand-off distance for second-stage forming

U_T of the component From Table 5a (M kg)	U_T of the first stage Dome from Table 8 (M kg)	U_T for second stage Col. 1- Col. 2 (M kg)	$t_0 Y \pi H^2$ for the component (M kg)	$t_0 Y \pi H^2$ for the first stage Dome (M kg)	$t_0 Y \pi H^2$ for the second stage Col. 4- Col. 5 (M kg)	$1 - \cos \phi$ From Eqn. 10 using values of Col. 3 and Col. 6	2θ From Eqn. 9	θ^2	η	W Based on Eqn. 3 (gm)	W Based on Eqn. 7 (gm)	W Rounded off (gm)	L/D From Eqn. 11	L Stand off Distance (mm)
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
344.7	243.9	100.8	199.6	164.5	35.1	0.0705	0.443	0.0491	0.39	18.06	18.06	18	1.26	87

formulae (Eqn. 7) owing to Noble & Oxley while equating the forming work done in creating the additional surface area with the amount of explosive energy utilised, totally ignores the strain hardening effect. But our results show that Noble & Oxley's approach is none the worse for it, because the efficiency of energy transfer turns out to be essentially the same either by Ezra's equation or by Noble & Oxley's formula, and further, the charge weights predicted by the two formulae for single stage forming, first stage forming and second stage forming are almost identical, indicating that either of the two formulae should serve well in arriving at the charge weight.

For computation of the stand-off distance, however one needs the Ezra's formulae (Eqns. 5 & 6) to calculate U_T, the total strain energy. It is seen from the forming results that in all the four cases, viz. (i) single stage forming (6 mm corner radii), (ii) single stage component forming (10 mm corner radii), (iii) first stage dome forming and (iv) the second stage component forming, the L/D ratio lies in the range of 0.89 – 1.26 which is close to 1.0, a value often reported[14] to have been used. It is to be noted, however, that the variation in stand-off distance that would arise from the use of L/D ratios differing as little as 0.89 and 1.26 can be significant in their effect on forming—as indeed it was—in view of the relatively small size of the component involved and the relatively high draw depth-to-diameter ratio. But an important deviation of L/D ratio from the above mentioned mean value of 1.0 cited in literature is by Ezra himself, who has based his strain energy derivations leading to Eqns. (5) & (6) on an assumption of $L/D = 0.167$. That our analysis here, using Eqns. (5) & (6) with L/D close to 1.0 should still lead to a valid prediction of the charge parameters, may be taken to mean a wider applicability of the ultimate form of Ezra's formulae. An additional point to be noted in the context of the question of stand-off distance is that the valid stand-off distance is to be obtained from the appropriate L/D ratio and the D pertaining to the appropriate diameter of die opening inclusive of die entry radii. Although Eqn. (11) has been found to be valid in predicting the L/D ratio for the limited variations of the forming trials in this investigation, its universal validity remains to be checked by further studies.

The result of forming second stage with these parameters, is shown in Table 11. The components formed with no cracking, (Fig. 9) and the taper of the vertical faces as shown in the taper analysis in Table 12 is found to be the least among the three variants tried, namely 6 mm die single-stage forming, 10 mm die single-stage forming and two-stage forming.

Table 11. Results of trials for second stage forming

Trial No.	Charge Weight (gm)	Stand-off Distance (mm)	Result of Forming
EF 8	18	87	Both steps formed well
EF 9	19	87	Both steps formed well

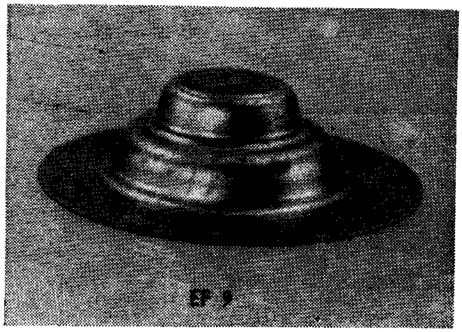


Figure 9. Components-second stage formed

Table 12. Measurement of taper on the formed components

Trial No.	Component Description	Charge Weight (gm)	Stand-Off Distance (mm)	Taper angle on the vertical face of 84 mm dia (deg)	Taper angle on the vertical face of 54 mm dia (deg)	Average of taper angles on vertical faces at 84 and 54 mm Diameters (deg)
EF 1	6 *R* Single stage Forming	37	90	8	10	9
EF 2	—do—	34	90	13	14	13.5
EF 3	—do—	40	90	6	6	6
EF 4	—do—	37	80	7	—	7.
EF 5	—do—	37	110	25	13	19
EF 6	10 *R* Single stage Forming	31	93	6	9	7.5
EF 7	First stage Dome Forming	25	93	—	—	—
EF 8	Second Stage Forming	18	87	5	8	6.5
EF 9	—do—	19	87	5	5	5

The taper of 6.5° observed in two stage forming could be decreased further to 5° by increasing the charge weight slightly from 18 gm to 19 gm, but at the expense of thinning which is found to increase from 42.4 to 45% (Table 13). In other words, with corner radii as sharp as 6 mm, the least observed taper close to 5° would correspond to maximum observed thinning of the component. Further improvement in taper by increasing charge weight can only be achieved at the risk of increased thinning. Thus, a compromise is to be struck between the degree of taper that could be permitted and the extent of thinning that could be tolerated depending on the ultimate application of the formed shape.

Table 13. Percentage thinning in the formed components

Trial No.	Component Description	Charge weight (gm)	Stand-Off Distance (mm)	Percentage thinning as measured in Fig. 1.
EF 1	6 *R* Single Stage Forming	37	90	43.0
EF 2	—do—	34	90	38.5
EF 3	—do—	40	90	46.0
EF 4	—do—	37	80	—
EF 5	—do—	37	110	40.8
EF 6	10 *R* Single Stage Forming	31	93	34.0
EF 7	First Stage Dome Forming	25	93	15.4
EF 8	Second Stage Forming	18	87	42.4
EF 9	—do—	19	87	45.0

From Table 13, it will be noticed that increasing the die corner radii to 10 mm has decreased the thinning effect to an extent lower than any of the other results of the component thinning. The least thinning (15.4%) observed in the first stage dome could thus be attributed to the total absence of any corners whatsoever in this shape. Thus die corner radius seems to be a dominant factor in causing thinning. Forming the component of 6 mm corner radii in two stages, has not only helped crack-free formation with least taper on the vertical faces, but also contained thinning to about the same extent as in single-stage forming in 10 mm die. The effect of having dynamic vacuum on thinning has not been studied in these experiments. The effect of hydrostatic head, which is kept constant, is also not within the scope of this study.

7. Conclusions

1. The efficiency of energy transfer in the under-water, stand-off, explosive forming using disposable plywood containers carried out under the conditions described here is found to be approximately 39 per cent.

2. The conversion, of non-spherical shape to be formed, into a dome of spherical segment of equal surface area enables one to apply well established formulae of dome for valid charge prediction.

3. The charge weights predicted through Ezra's approach that accounts for strain hardening, and Noble & Oxley's approach that ignores strain hardening effect, are almost identical.

4. The stand-off distance L, for a given set of experimental conditions can be predicted with reasonable accuracy from the equation,

$$\frac{L}{D} = \frac{1}{2 \tan\left[\cos^{-1}\left(1 - \frac{2\, t_0\, Y H^2}{\pi\, U_T}\right)\right]}$$

5. A die-corner radius of 6 mm in shaped contours such as the one chosen in our work is too sharp to be reproduced in single-stage explosive forming with crack-free results in 2 mm thick, low carbon steel sheet. A more generous arbitrary radius of 10 mm in the corners of the subject component has fully eliminated cracking in single shot forming, but could not fully eliminate the problem of taper in the vertical faces.

6. The taper in vertical faces of the component is the least for two stage forming among the three variants tried, namely, singlestage forming in 6 mm die, single stage forming in 10 mm die and two stage forming, the first stage being a dome shape.

7. The taper is virtually eliminated only at the expense of significant thinning in the blank thickness; the least taper obtained corresponds to maximum thinning that occurred among the trials conducted.

Acknowledgement

The authors gratefully acknowledge the permission of Dr P. Rama Rao, Director, Defence Metallurgical Research Laboratory, Hyderabad to publish the results of this work.

References

1. Pearson, J., *Journal of Metals*, **12** (1960), 673–681.
2. Rinehart, J. S. & Pearson, J., 'Explosive Working of Metals', (Pergamon Press, London) (1963), p. 9.
3. Alting, L., 'Explosive Forming of Domes, Proceedings of the Third International Conference of the Centre for High Energy Forming, Vail, Colorado', 1971.
4. Ezra, A. A. & Malcolm, M., An Investigation of the Effect of Explosive Stand-Off Distance on the Forming of Metal Blanks, First International Conference of the Centre for High Energy Forming, Estes Park, Colorado, 1967, 2, (6), 6.4.1—6.4.20.
5. Ezra, A. A., 'Principles and Practice of Explosive Metal Working', (Industrial Newspapers, London), 1973, p. 86.
6. Marin, J., 'Behaviour of Engineering Materials' (Prentice-Hall), 1962.
7. Wilson, F. W., 'High Velocity Forming of Metals', A. S. T. M. E. (Prentice-Hall), 1964, p. 180.
8. Tobias, S. A., Development of an Explosive Sheet Forming Machine, Proceedings of the Fourth International Machine Tool Design and Research Conference, (Pergamon Press), 1963.
9. Noble, C. F. & Oxley, P L. B., Estimating Charge Size in Explosive Forming of Sheet Metal, Proceedings 5th International Machine Tool Design and Research Conference, Birmingham, 1964, p. 332.

10. Alting, L., Explosive Forming of Metal Blanks, Ph.D. Thesis, Department of Mechanical Technology, Technical University of Denmark.
11. Ezra, A. A., 'Principles and Practice of Explosive Metal Working', (Industrial Newspapers, London), 1973, p. 81.
12. Ezra, A. A., 'Principles and Practice of Explosive Metal Working', (Industrial Newspapers, London), 1973, pp. 75 & 80.
13. Ezra, A. A., 'Principles and Practice of Explosive Metal Working', (Industrial Newspapers, London), 1973, p. 79.
14. Davies, R. & Austin, E. R.. 'Development in High Speed Metal Forming', (Machinery Publishing Co., London), 1970, p. 192.