AN EXPERIMENTAL INVESTIGATION INTO THE EXPLOSIVE FORMING OF SQUARE BLANKS USING PERFORATED DIES

by

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ABSTRACT

The explosive forming of steel blanks into a perforated square die of side 200 mm and depth 40 mm has been investigated. The results show that blanks can be successfully formed with perforated dies and that the smaller the percentage of perforation and vent size, the greater the quantity of explosive needed for successful forming. The results also show that the indentation of deformed blanks at the vents is more prominent when large sized vents are used, and decreases with increase in standoff distance. The results also show that better die filling at the corners of the die is obtained if more vents are provided at the corners of the die.

LIST OF SYMBOLS

E_P - plastic work done in deforming blank
t - initial blank thickness
A - area of blank
ΔA - increase in area of deformed blank.
Y - yield stress of blank material in simple tension
H - slope of work hardening part of stress-strain curve of blank material.
E - Energy of explosive available for blank deformation
m - mass of explosive charge
η -efficiency of energy transfer medium
$\omega, \omega_1, \omega_2$ - various solid angles sub tended at the centre of the charge
l - standoff distance

w - elastic base plate deflection
V - elastic deformation energy of plate
D - flexural rigidity of plate
ν - Poisson's ratio
W_o - maximum plate deflection
a - half of side *of* square die
M_{max} - maximum bending 'moment
M_o - moment to form plastic hinge
q - load per unit area of plate
h_o - die base plate thickness
P_m - maximum pressure due to shock wave
R - distance from centre of deformation
K,β - constants of the explosive

1. INTRODUCTION

Explosive forming of metals has been used for specialized forming operations for about three decades. Most of these operations have involved the forming of very large metal parts which cannot be handled by conventional methods or for very special materials such as the forming of very brittle materials. In the forming of metal blanks into precise shapes, it has been necessary to use dies. In the past the use of dies necessitated the use of a vacuum pump to remove the air between the blank and die so that the air does not prevent the blank from taking the shape of the die. If the air between the blank and die escapes during forming, complete die filling will be obtained and there will be no need for a vacuum pump. Some preliminary studies have been carried out in this vein. Hardee [1] carried out investigations into the use of perforated dies in the forming of hemispherical domes. He obtained successful forming with the dies and was able to measure the forces to which the perforated die was subjected during the operation. Aku [2] reported some successful experiments in the forming of circular and square plates using vented dies. The experiments indicated good forming of circular blanks, but showed that further studies were needed in the forming of square plates. The study being reported was therefore carried out to determine:

(i) The amount of perforation required for successful forming of square blanks.

(ii) The optimum size of vents, if any

(iii) The best distribution of vents in the perforated die.

Before carrying out actual tests, the working medium for the explosive had to be decided upon and the forming die designed. In standoff operations, the energy delivered to the work-piece can be computed by three different methods the energy method, the geometrical method and the impulse method. The three methods have been discussed at length by Ezra [3] and Cook *[4].* The geometrical method is the simplest to use. Its results are nearly as accurate as the other methods. The method is based primarily on the specific energy of the explosive and the solid angle subtended by the workpiece at the centre of the charge. Because of the simplicity of the geometrical method compared to the other methods, it was used to determine the quantity of explosive necessary to produce the deformation of the blanks. From a knowledge of the amount of explosive required for the forming operation the die was designed to withstand the forces involved.

2. DETERMINATION OF THE MASS OF EXPLOSIVE REQUIRED.

Before the amount of explosive necessary to produce the deformation is computed, it is necessary to determine the energy required for the plastic deformation of the blank so that it completely fills the square die of side 200 mm and depth 40 mm. The simplest method of determining the deformation energy of the blank is by using the method of Noble and Oxley [5]. The material is assumed to be under the action of biaxial stresses and
edge pull-in is negligible. Aku [6] has shown that the assumption on edge pull-in is valid for the shallow draw depths, as in the case being reported in this paper. Noble and Oxley [5] 'show that the work done E_p is given by the equation:

$$E_p = t\Delta A\left(Y + \frac{1}{2}\frac{\Delta A}{A}H\right) \qquad (1)$$

where t is the plate thickness, A is the initial area of the plate, ΔA is the increase in surface area of the deformed plate, Y is the yield stress of the material in simple. tension and H is the slope of the work hardening curve of the material. Y and H were determined by subjecting a strip of the blank material to simple tension test to instability in the as machined condition.

Having determined the energy required for the deformation of the plate, the mass of the explosive charge required with water as the working medium was calculated. Water was chosen as the working medium as it is efficient and controls the amount of noise created by the explosion.

In the geometrical method, the energy available for deformation of the blank as a fraction of the total energy of the point charge is the ratio of the solid angle subtended by the blank at the centre of the charge of the charge to the solid angle subtended at the centre of the charge of the charge to the solid angle subtended at the center of the charge by a sphere enclosing the charge. If η is the efficiency of energy transmission by the working medium, m is the mass of the charge and e is the specific energy of the explosive, then the energy utilized for the deformation E is given by

$$E = m.e.\eta\,\frac{solid\ angle\ given\ by\ plate}{solid\ angle\ by\ sphere}$$

Or

$$E = m.e.\eta \frac{solid\ angle\ given\ by\ plate}{4\pi}$$

The solid angle subtended by the plate at the centre of the charge is determined from consideration of Fig. 1.

Fig.1. shows the square blank of sides a with charge centre O. The charge is centrally placed above the blank and the distance of 0 above the blank is λ. The solid angle ω substended by the square ABCD at 0 is equal to the sum of the solid angles ω_1 and ω_2 subs tended by the triangles ABC and ACD at 0 respectively. Let the planes AOC, DOC, DOA intersect the unit sphere centre 0, and the spherical triangle A'D'C' is of sides a ', d' and c'. Let the area of triangle ADC by A_1 and the lengths of AO, DO and CO be p, q and r respectively. According to the method of Edwards [7], the solid angle ω_1 is given by the equation

$$sin\frac{\omega_1}{2} = \frac{4\ \lambda\ A_1}{8\,pqr\cos\frac{a'}{2}\cos\frac{d'}{2}\cos\frac{c'}{2}} \qquad (3)$$

Equation (3) enables the solid angle ω_1 to be computed. Since the plate is square, it follows that $\omega_1 = \omega_2$ and the required solid angle is given by

$$\omega = 2\omega_1 \qquad (4)$$

The energy transferred to the plate is given by

$$E = m.e.\eta\frac{\omega}{4\pi} \qquad (5)$$

To determine m, let E equals E_p, hence

$$me\,\eta\frac{\omega}{4\pi} = t.\Delta A\left(Y + \frac{1}{2}\frac{\Delta A}{A}H\right)$$

Or

$$m = \frac{4\Pi t\Delta A\left(Y + \frac{1\Delta A}{2\,A}H\right)}{\omega\, e\, \eta} \qquad (6)$$

The working medium is water and in accordance with Ezra [3] η is taken as $\frac{1}{2}$. The specific energy of the explosive obtained. from tables by Ezra [3] and equation (6) was used to determine the quantity of explosive required to produce the necessary blank deformation.

In determining m, the standoff distance λ was chosen to give the most uniform strain distribution in accordance with the findings of Ezera [3], who showed that for circular blanks the best ratio of standoff distance to the diameter of the plate is 1/6. In the case under study the standoff distance was chosen as 1/6 of the mean "diameter" of the square plate (i.e. the diameter that has the same area as the square).

3. DESIGN OF THE DIE BASE PLATE

Having determined the quantity of explosive necessary for the deformation, it is necessary to design the die that will withstand the shock resulting from the explosion of the charge. The only portion of the die which needs to be treated analytically is the die base plate. The die base plate was treated as a plate clamped at the edges and subjected to a uniformly distributed load. The analysis of the deflection of the die base plate was carried out using the theory of Timoshenko [8] and the principle of virtual displacement. The object of this analysis is to ensure that the plate deformation is elastic. The plate deflection w is given by the equation

$$w = w_o\cos\left(\frac{\pi x}{2a}\right)\cos\left(\frac{\pi y}{2a}\right) \qquad (7)$$

and the energy of deformation V is given by

$$V = \frac{1}{2}D\iint\left[\left(\frac{\delta^2 w}{\delta x^2} + \frac{\delta^2 w}{\delta y^2}\right)^2 - 2(1-V)\left(\frac{\delta^2 w}{\delta x^2}.\frac{\delta^2 w}{\delta y^2}\right) - \left(\frac{\delta^2 w}{\delta x \delta y}\right)^2\right]dxdy \qquad (8)$$

Using the principle of virtual displacement in conjunction with the energy

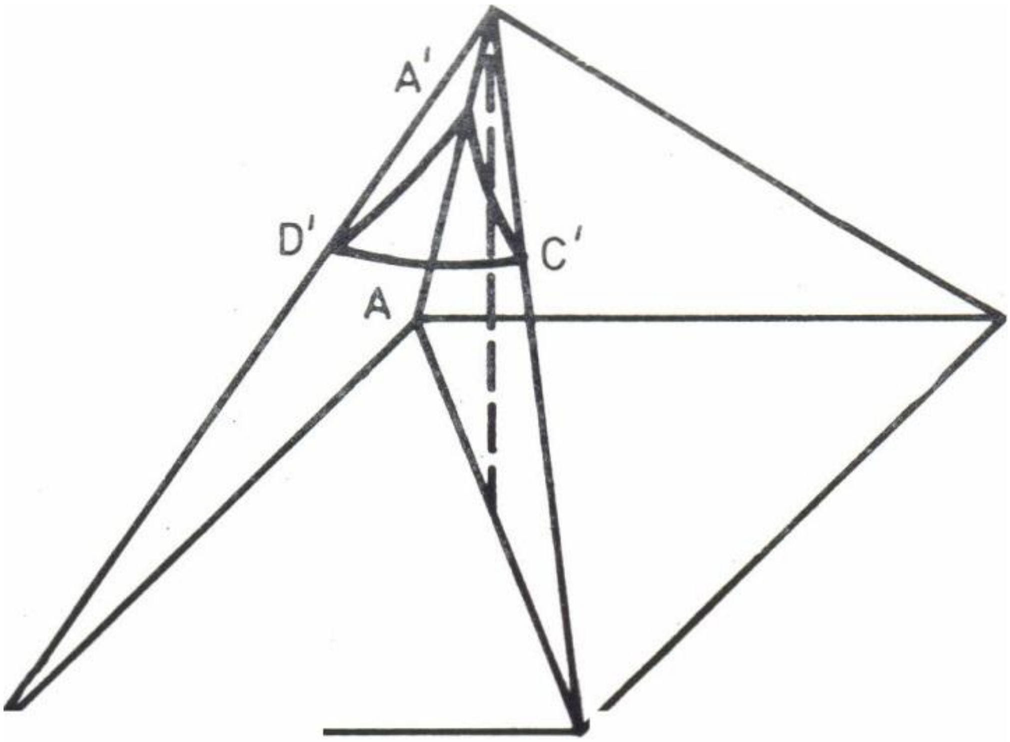

Fig. 1. Solid angle substended by square blank ABCD at charge center O

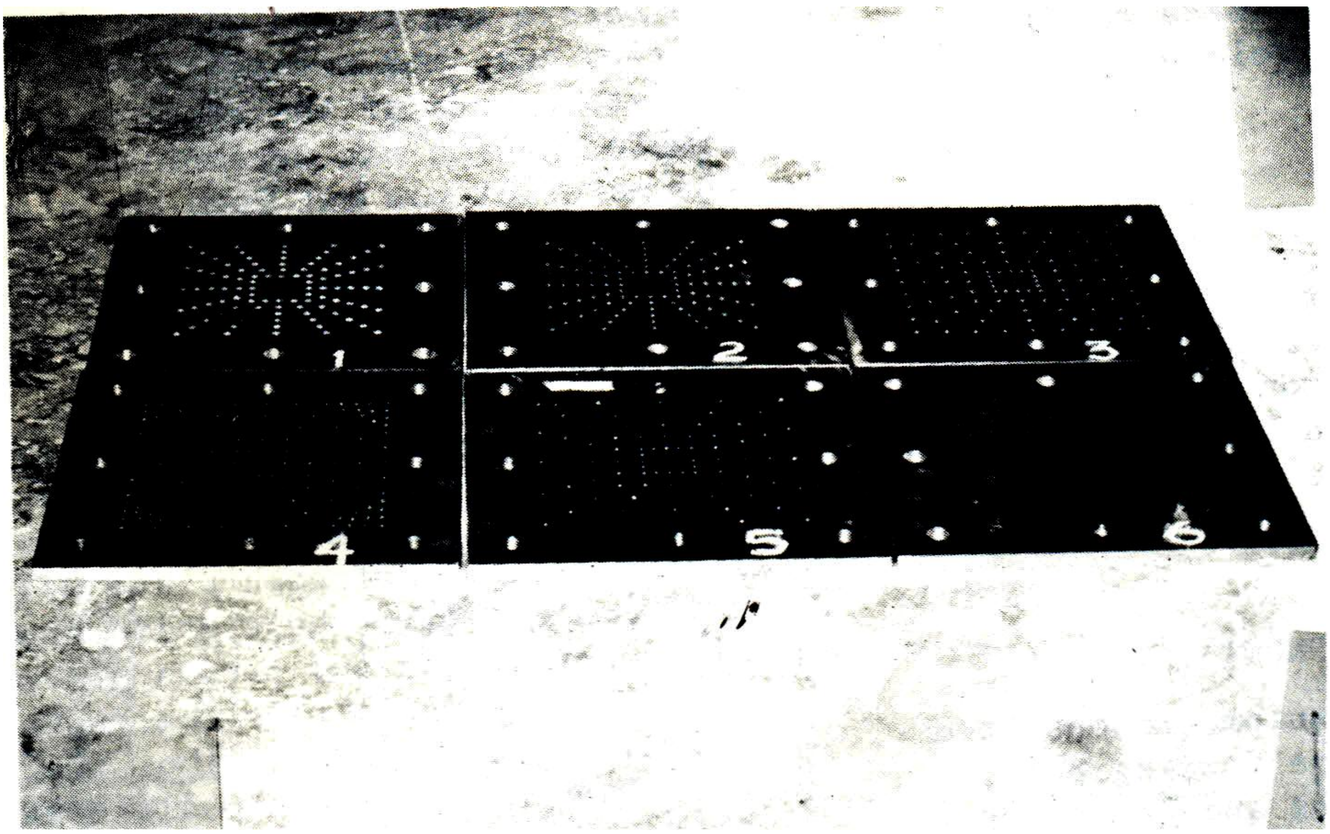

Fig. 3. Samples of Die base plates with various vent distributions

equation, it can he shown that the maximum bending moment M_{max} in the plate is given by

$$M_{max}/unit\ length = (1+V)\frac{16a^2q}{\pi^4} \quad (9)$$

where q is the load per unit area of the plate. For unit length of the plate, the maximum permissible bending moment is the moment that produces a plastic hinge M_0. This moment is equal to $Yh_o^2/4$. where h_o is the thickness of the plate. Hence for elastic deformation of the plate,

$$\frac{Yh_0^2}{4} = \frac{16(1+V)a^2q}{\pi^4} \quad (10)$$

In equation (10) we need to estimate the maximum pressure q which will be used for the evaluation of h_o Based on the experience of Aku [2], it was assumed that a maximum of 5 per cent of the energy delivered to the plate is transferred to the die base plate. From this reasoning it is assumed that the maximum pressure on the plate is 5 per cent of the maximum pressure P_m produced by the charge on the blank by a charge of mass m at distance R. This pressure p_m is computed according to the empirical formula of Ezra [3] which takes into account the reloading phenomenum. The Ezra formula is:

$$P_m = K\left(\frac{m^{\frac{1}{3}}}{R}\right)\beta \quad (11)$$

where K and β are constants for the explosive. For actual computation of the plate thickness, a factor of safety of 10 was used to take into account the perforations on the base plate which, ideally, is not supposed to carry any of the load from the blank.

4. DESCRIPTION OF EQUIPMENT

The experimental equipment consisted of the die assembly, the forming pool, electric detonating caps and detonator, a balance and test specimen. The die assembly is presented in Fig.2. It consists of the die block machined from a mild steel block which is 40mm thick. The block is 480mm by 480mm and the die space is 200mm by 20Omm. Fixed to the die block are four hooks to which a steel rope was attached "for the suspension of the die assembly in the forming pool. A 30mm long skirt was also fixed to the die block. The skirt was used to trap air between the die base and the blank to prevent water from occupying the space. The die base whose thickness was computed in the previous section was designed so that it could be replaced easily and also allowed the effects of the area ratio, vent distribution and vent size to be studied. Die base plate of various vent distribution, sizes-and area ratio were made. A sample of some of the die base plates is shown in Fig.3. The die clamping ring was made from mild steel plate. It was held to the die block by 8 bolts and it carried the standoff bars from which the explosive charge was suspended. The rubber gasket between the blank and die block prevented the air trapped by the skirt from leaking away.

The forming pool which is of 3m diameter by 4m deep is of concrete lined with 5mm thick steel plate. It has a loading frame complete with tackle capable of carrying 1 tonne load.

5. EXPERIMENTAL PROCEDURE

Before the design of the die was carried out, the stress-strain characteristic curve of the steel material in simple tension was determined. A strip of the material was cut into the standard tensile specimen shape and the test was carried out in the universal testing machine with the specimen in the as machined state.

Blanks were then cut to sizes of 340mm by 340mm and were prepared to fit into the die. 1Omm by 10mm grids were put on one side of each plate using a rule and scriber. These grids enabled the plate deflection and strain distribution to be determined. After the rubber gasket had been placed in position, the blank and clamping ring were positioned and the bolts were tightened to give uniform clamping pressure on the plate.

The amount of explosive required was measured for the appropriate standoff distance and was covered with celotape after provision had been made for the insertion of the detonation cap. The die was suspended in the tackle and the charge

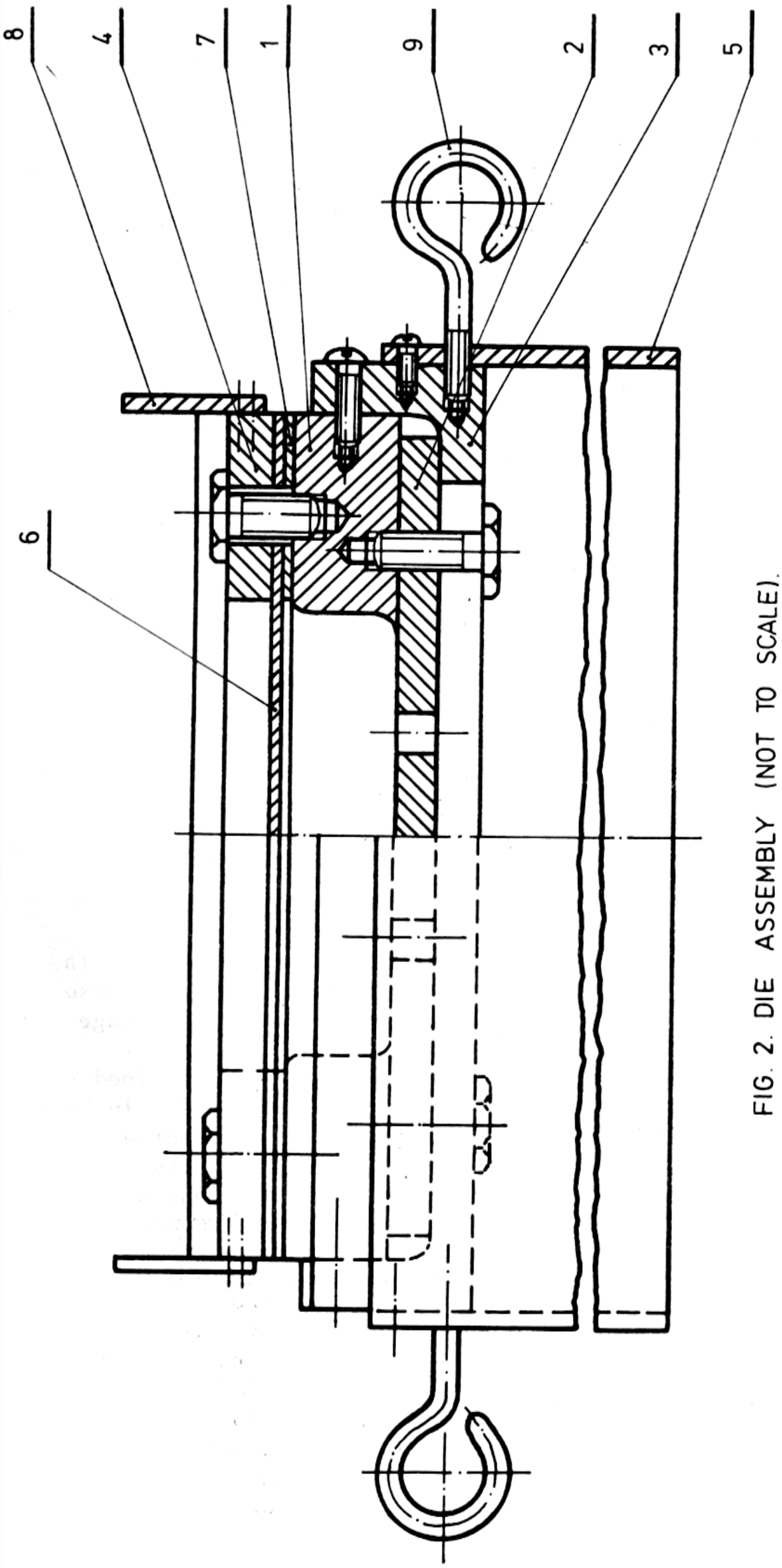

FIG. 2. DIE ASSEMBLY (NOT TO SCALE).

1 - DIE BLOCK
2 - VARIABLE BASE
3 - BASE
4 - CLAMPING RING
5 - SKIRT
6 - BLANK.
7 - RABBER GASKEL
8 - STANDOFF BAR
9 - HOOKE

was placed in position and was armed with 'the detonation cap. The assembly was then carefully lowered into the forming pool till the charge was about 50cm below the water surface before it was detonated. The charge was then detonated using the battery-operated detonator. After retrieving the blank from the die assembly, its profile was measured in a specially designed rig and some of the blanks were cut in half and the thickness strain distribution was measured. In order to ascertain the repeatability of the study, each test was carried out on two blanks.

6. RESULTS

The stress-strain characteristic curve of the material is presented in Fig 4. It shows that the material work-hardens significantly. Based on the analysis, the quantity of explosive necessary to produce the required deformation of the blank is 10gms of 70/30 dynamite for a standoff distance of 33.3mm and 10.8 and 12.lgms for standoff distances of 40mm and 50mm respectively.

Figure 5 shows typically formed plates. Plates marked 1,2,4,5 and 7 are well formed but numbers 3 and 6 show incomplete die filling whilst number 8 is badly formed as a result of the base plate without vents. The final shape of plate number 8 of Fig.5 has no bearing on the flat bottom die shape showing clearly air has been trapped between die base and the blank and the necessity for perforations on the die base.

The effects of the percentage perforation (area ratio) and size of holes are presented in Table 1 for the hole patterns of base plate number 2 of Fig.2 which has 96 holes. The indentations in Table 1 refer to the marks made on the plate as the excess energy of the plate tries to blank parts of the plate through the vents in the die base.

The results of Table 1 show good forming of the blanks and good blank filling, except at the die corners. Tests were carried out for the same area of perforation with the hole distribution altered in the forms of numbers 3 and 4 of Fig.2 for hole diameters of 3mm. For standoff distances of 33.3mm and 10.6gm charges, blanks were well formed with light indentation and slightly improved die filling at filling at the carriers.

Blanks formed with die base plate number 5 of Fig.2 which has 80 holes were as good as the previously formed blanks, but the quantity of explosive to form -the blanks was increased.

The profile of a typical well-formed blank is presented in Fig.6. Edge pull-in for the plate of Fig.6 is-presented in Fig. 7. It was observed that edge pull-in was not as large in plates that did not fill the die as in plates which filled the die well. Both Figs.6 and 7 are for plate number 3 of 'Fig.2. Typical strain distribution for a well formed plate and the displacement distribution for the blank of Fig.6 are presented in Figs.8 and 9 respectively.

7. DISCUSSION OF RESULTS

The mass of explosive required for deformation as calculated was sufficient for the deformation of the blanks. This shows that-the method used for determination of the energy of plastic deformation of the blank and the geometrical formula used for determination of the quantity of explosive are sufficiently accurate for the work being reported.

7.1 Effect of Percentage Perforation

Blanks formed with die bases with 12 percent perforation (8mm diameter holes) were well formed. Die bases with 4.7 and 4 percent perforation were also well formed. With the lower percentage perforations of 3.0 and 1.7 percent complete die filling was not obtained for the normal quantity of explosive. In those cases, the charge weight was increased to obtain die filling. These results show that for percentage perforations of 4 and above, the vents were large enough for air to escape within the short time of the deformation. For the smaller vents, extra explosive was needed to force the trapped air out within period of deformation. The results, however, show very clearly that successful forming cannot be carried out with zero perforation as trapped air cannot escape.

Fig.5. Typical deformed plates for various base loads

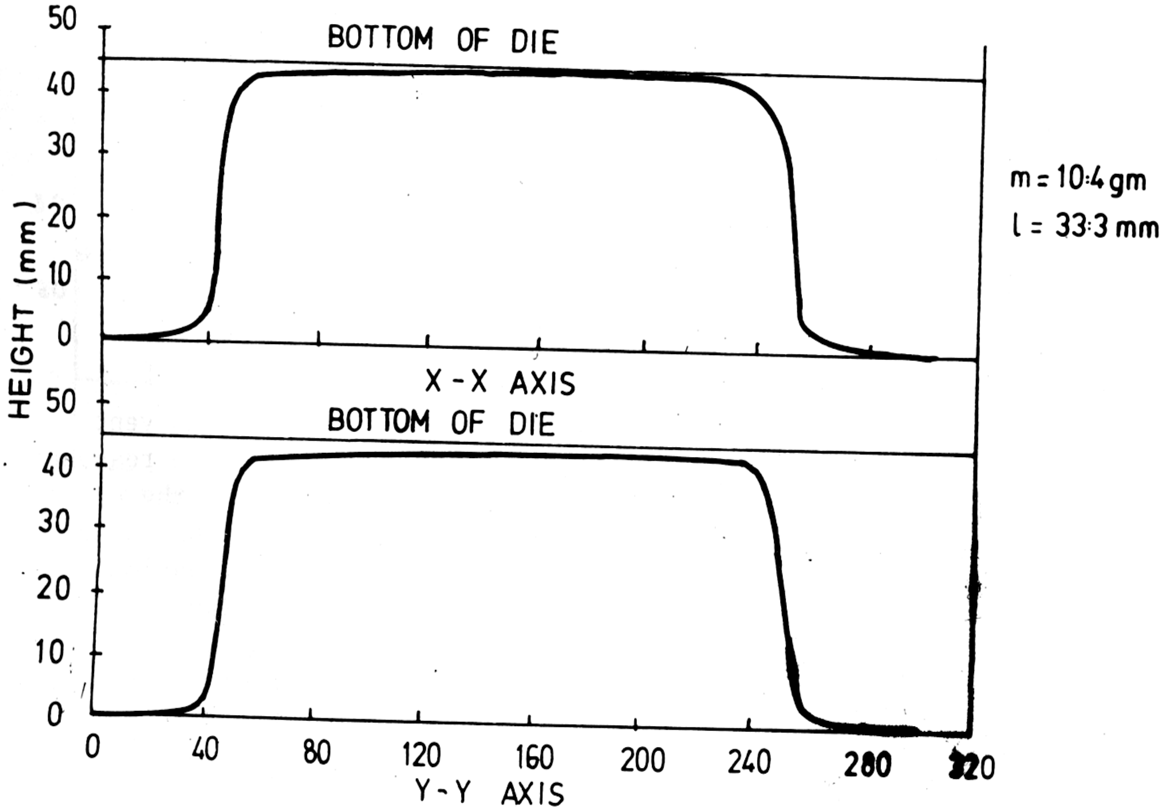

Fig. 6. Deformed blank profile in X -X and Y - Y direction for die base plate No. 2 of fig. 2.

Table 1. Effects of Area Ratio and Hole Sizes on Blanks

Diameter of holes (mm)	Percentage area of perforation	Standoff distance (mm)	Blank thickness (mm)	Mass of explosive (gm)	Remarks
0	0	33.3	.71	10.0	Very poor die filling. Final shape of blank does not resemble die shape
4	3.0	33.3	.71	10.0	Blank not well-formed due to poor die filling
4	3.0	33.3	.71	10.4	Blanks well-formed with light indentations. Die corners not filled.
5	4.7	33.3	.71	10.4	Die filling complete but indentations were observed
3	1.7		.71	10.4	Blanks did not completely fill the die
3	1.7	33.3	.71	10.6	Blanks well-formed with light indentations
5	4.7	40.0	.71	10.8	Blanks well-formed with indentations
5	4.7	50.0	.71	12.1	Blanks well-formed with Little indentations

7.2 Effect of size of Vent

Vents of 8mm, -mm, 4mm and 3mm were used. It was found that with the large diameter (8mm and 5mm) vents, serious indentation of deformed blanks occurred. With the smaller vent diameters, indentation was non-existent or *very* light. It is believed that with larger diameter vents, the air was forced out very quickly and the plate had more residual energy which was used in further deformation of the blanks when they have come into contact with the die base plate. In one test case, when more explosive than necessary was used, the blanking of the work piece was observed at its central region. Since indentation destroys the surface finish of the deformed blanks, it is necessary that perforated dies used should have as small vents as possible.

7.3 Effects of Vent Distribution

Generally, all the various vent distributions investigated gave reasonably well formed blanks, except at the corners where incomplete die filling was observed. The choice of the vent distribution was based on the experience of Aku [2] in his previous study. Better die filling was obtained at the corners from die base plates which had more perforations at the corners. Since the blank has a higher initial velocity from the detonation of the charge, the blank centre reaches the base before the sides and corners, hence some of the air at the centre gets pushed to the sides and corners and prevent

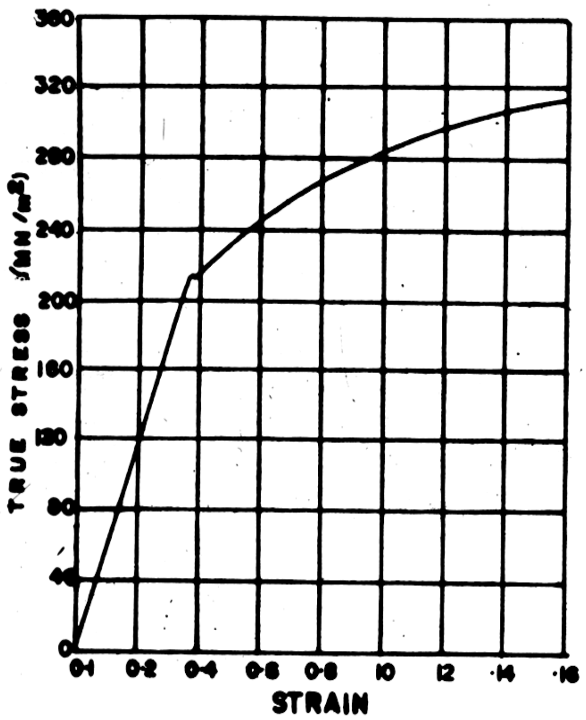

Fig. 4. Stress strain curve of blank material

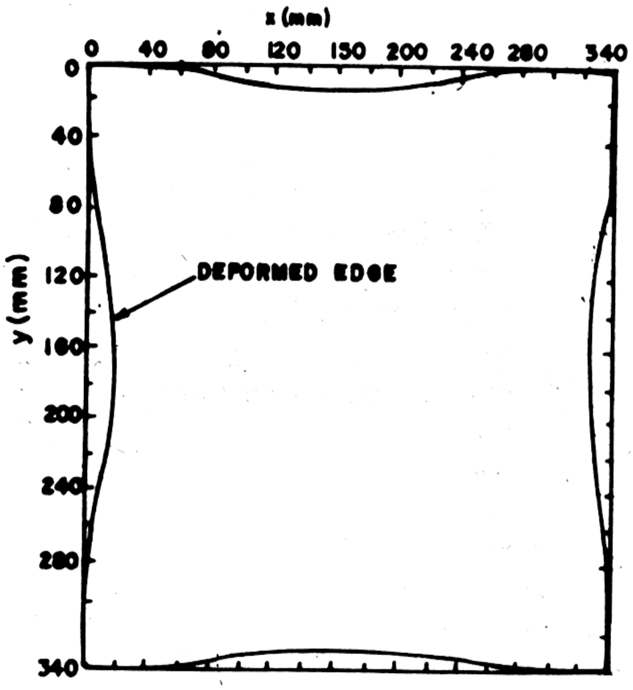

Fig. 7. Edge Pull - in blank of Fig. 6.

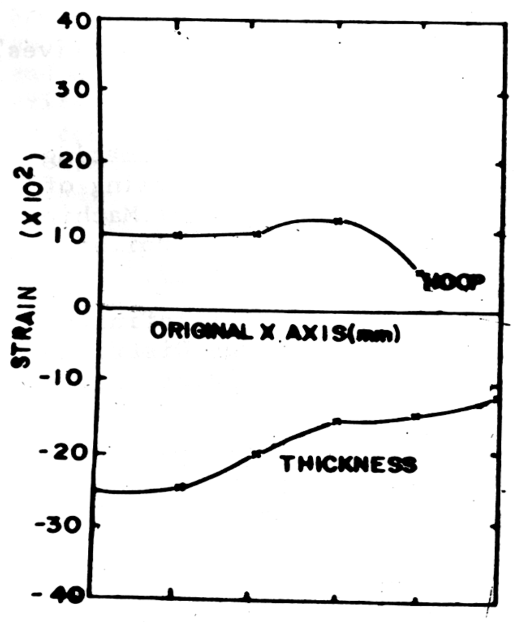

Fig. 8. Strain distribution for well-formed blanks.

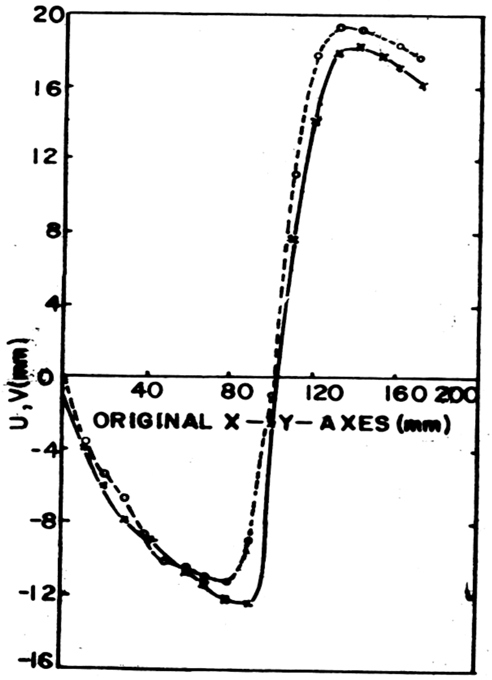

Fig. 9. Displacement distribution for well-formed blank.

better die filling at those locations. The mechanics are also partially responsible for incomplete die filling at the corners.

7.4 Effect of Standoff Distance

For each of three different die base plates with 5mm diameter vents, blanks were tested with charges at standoff distances of 33.5mm, 40mm·and 50mm. In all cases tested, good die filling was obtained and it was found that indentation was reduced with the increase in standoff distance. The reduction in indentation with larger standoff distances is due to the fact that with larger standoff distance, the initial velocity distribution of the blank is more uniform and hence the central portion of the blank which has the most severe indentation has less energy left to produce indentation.

The typical strain distribution curve for a well-formed blank generally shows greater strain at the centre of the plate. This illustrates that there is stretching at the plate centre, though under the test conditions this thinning is not serious. The strain and displacement distribution curves are not smooth due to the fact that the indentations made accurate measurements of the blank thickness and displacement impossible.

8. CONCLUSIONS

From the study reported the following conclusions could be drawn:

(i) In order to form a blank successfully into a die, the air between the blank and die has to be removed.

(ii) Vented dies can be used to remove the air between the blank and die instead of using a vacuum pump to remove the air, thus saving in production costs.

(iii) When vents are being made on the die, it is important that more vents should be located at the sides and corners of the die than at the central portion of .the die if a single point charge is used for the deformation.

(iv) In venting the die, the percentage, perforation should be arrived at by using a larger number of small diameter vents rather than large diameter vents as smaller vents-produce better surface finish by suppression of indentations.

(v) Percentage perforation could be as low as two per cent but for low percentage perforation, a higher amount of explosive is required for complete die filling.

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