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A study on the UNDEX cup forming

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Analysis and modelling

ABSTRACT

Purpose: This work investigates the use of the underwater explosion (UNDEX) for the free and plug assisted cup forming processes.

Design/methodology/approach: A 3D finite element model is built to simulate the process of the UNDEX cup forming using ABAQUS finite element code. Johnson-Cook (JC) material plasticity model is used to represent strain rate sensitivity of the used materials. Johnson- Cook damage criterion is employed to detect the onset of damage in the cup forming process.

Findings: Both relatively hard and soft plugs are considered and the effects of using different plug materials on cup profile, strains and the limiting drawing ratios are given. The onset of damage in this process is also indicated. The results suggest that a relatively hard plug can enhance the control of the cup shape and the uniformity of strain distribution leading to increased limiting drawing ratio.

Research limitations/implications: This work suggests a methodology for the prediction of shape, different strain distribution, the limiting drawing ratio and the energy required for UNDEX cup forming process.

Practical implications: This study could be useful in non-conventional high energy rate forming industry.

Originality/value: The study reveals the possibility of producing flat-bottomed cup by the relatively hard plug assisted UNDEX forming technique.

Keywords: Underwater explosion (UNDEX); Plug assisted cup forming; Johnson-Cook (JC) material; ABAQUS finite element code

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1. Introduction

Explosive forming is a technique that is generally adopted for sheet metal forming operations involving very large, usually symmetric parts. The method is essentially dynamic and the forming is induced by exposing sheet metal surface to an incoming pressure wave generated by explosion [1, 2]. Yasar et al [3, 4] conducted both experimental and numerical investigations of aluminium cylindrical cup drawing using gas detonation device. The forming process simulation is carried out in 2D and 3D computational models using the explicit dynamic analysis code module incorporated ANSYS/LS-DYNA computer software. Theoretical and experimental results showed approximately 80-90% similarities in formability. El Mokadem developed a dynamic forming limit diagram for this process [5].

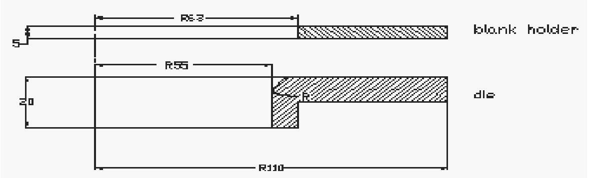
Wijayathunga et. al [6] developed a FE model to simulate the experimental tests for the impulsive deep drawing of a brass square cup with the presence of a soft lead plug. The loading of the assembly was achieved by the detonation of an underwater high explosive. The formability of the brass plate in the absence of the lead plug resulted in material instability and uneven material thickness over the formed region causing rupture. The presence of the lead plug enabled a higher ratio of draw ability and a better uniformity in thickness of the formed dome. Akbari et al. [7] studied the free UNDEX forming of aluminium circular plates experimentally and analytically, using a central explosive charge on 2024 aluminium sheet. All experiments carried out were simulated using FEM with Johnson-Cook (JC) and Zerilli-Armstrong (ZA) plasticity models. The results indicated the importance of using a proper model for the effect of strain rate.

The present work investigates the use of the underwater explosion (UNDEX) for the free and plug assisted cup forming processes.

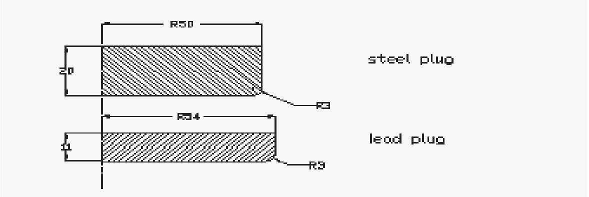
A 3D finite element model is built to simulate the process of the UNDEX cup forming using ABAQUS finite element code. Johnson-Cook (JC) material plasticity model is used to represent strain rate sensitivity of the used materials. Johnson- Cook damage criterion is employed to detect the onset of damage in the cup forming process.[8]

2. Finite element model

A 3D finite element model is built to simulate the UNDEX cup forming processes. Eight node, linear brick, reduced integration, hourglass control continuum element of the type C3D8R available in ABAQUS element library is used in the analysis for the blank , the plug, and the die. The blank is modelled in all cases with 4 elements in the thickness direction. The contact between blank holder-work piece, and work piece - die is modelled using Coulomb friction of, 0.05 [6,7]. The analysis considers a fixed standoff distance, R= 250 mm. Different parameters are considered including die opening diameter, D=70, 90 and 110 mm, die corner radius, rd = 6, 8, 10 and 12 mm, blank holder gap Δ = 0.0.5 and 1 mm, work piece thickness, t =1,and 2 mm, and charge weight, W. The target in all cases is to find out the working parameters leading to maximum blank drawing ratio, D_b /D which ensures complete successful cup forming process.



(a) Die and Blank holder



(b) Used plugs

Fig.1. Sample model geometry

Fig. 1 shows the geometry of die, blank holder, the soft lead and the steel assisting plugs. Notice that both the lead and steel plugs have the same mass.

2.1. Material modeling

Johnson-Cook (JC) material plasticity model is used to represent strain rate sensitivity of the sheet metal used in the model [3,4]. The (JC) hardening is particular type of isotropic hardening in which the static yield stress, σ_y, takes the form [8]:

$$\sigma_y = \left[A + B\left(\bar{\varepsilon}^{pl}\right)^n\right]\left[1 + C\left(\frac{\dot{\bar{\varepsilon}}^{pl}}{\dot{\varepsilon}_o}\right)\right]\left(1 - \hat{\theta}^m\right) \tag{1}$$

where, $\bar{\varepsilon}^{pl}$ is the equivalent plastic strain and *A*, *B*, *n*, C and *m* are material parameters measured below the transition temperature, $\theta_{transition}$. $\hat{\theta}$ is the non-dimensional (or homologous) temperature defined as:

$$\hat{\theta} = \left(\theta - \theta_{transition}\right) / \left(\theta_{melt} - \theta_{transition}\right) \tag{2}$$

for $\theta_{transition} \le \theta \le \theta_{melt}$

Johnson-Cook damage criterion is a special case of the ductile fracture criterion in which the equivalent plastic strain at the onset of damage is given by [8]:

$$\bar{\varepsilon}_D^{pl} = \left[d_1 + d_2 exp\left(-d_3\eta\right)\right]\left[1 + d_4 ln\left(\frac{\dot{\bar{\varepsilon}}^{pl}}{\dot{\varepsilon}_o}\right)\right]\left(1 + d_5\hat{\theta}\right) \tag{3}$$

where, d_1-d_5 are failure parameters and $\dot{\varepsilon}_o$ the reference strain rate. The failure criterion is met when the state variable, ω_D, is equal to unity:

$$\omega_D = \int \frac{d\bar{\varepsilon}^{pl}}{\bar{\varepsilon}^{pl}\left(\eta, \dot{\bar{\varepsilon}}^{pl}\right)} = 1 \tag{4}$$

In the present model, Johnson-Cook material model is adopted based on published data. Table 1 shows the AA 5083-H116 Aluminium alloy JC model constitutive parameters as taken from [9] as well as the mechanical properties of the two plug materials under consideration.

2.2. Load representation

Load is represented using exponentially decaying pressure history. Calculated pressure-time curve is used based on impulse approach introduced by Ezra [10]. The model of free field pressure loading is considered as follows:

$$P = P_0 e^{-t/\theta} \tag{5}$$

where P_0 is the peak pressure and θ is the decaying time, which are given by:

$$P_0 = A\left(\frac{W^{1/3}}{R}\right)^{\alpha}, \qquad \theta = k_\theta \times W^{1/3}\left(\frac{W^{1/3}}{R}\right)^{\gamma} \tag{6}$$

Then, the actual pressure is given by

$$P_t = 2 \times k_\theta \left(\frac{W^{1/3}}{R}\right)^{\alpha} e^{-t/\theta} \tag{7}$$

Table 1.
JC constitutive parameters for aluminium sheet metals and Mechanical properties of material used in the model

AA 5083-H116 Aluminium [9]		Units
A (σ_y)	167	MPa
B	596	MPa
n	0.551	
C	0.001	
$\dot{\varepsilon}_o$	1	
m	0.859	
T_{ref}	293	^oK
T_{melt}	893	^oK
E	70	GPa
ν	0.3	
ρ	2700	kg/m^3
d_1	0.0261	
d_2	0.263	
d_3	-0.349	
d_4	0.147	
d_5	16.8	
Mild Steel (Die, Plug [8]		Units
σ_y	300	MPa
E	207	GPa
ν	0.3	
ρ	7850	kg/m^3
Lead [6]		
σ_y	30	MPa
E	36.5	GPa
ν	0.425	
ρ	11340	kg/m^3

Table 2 shows the coefficients of TNT explosive material used in the present study.

Table 2.
TNT material constants for impulse method [11]

	$A \times 10^6$	$\mathcal{A}$	$k_\theta \times 10^6$	$\gamma \times 10^{-3}$
TNT	52.16	1.13	96.5	-0.22

3. Results and discussions

The developed finite element model was verified by solving the bi-axial explosive stretch forming of aluminum circular sheets. The model results show a good agreement with the experimental results of the same case [5, 12].

3.1. Free UNDEX cup forming

Here we focus our attention to the effect of some of the process parameters on the UNDEX cup forming. Figure 2 shows the effect of die corner radius (rd) on the cup profile for die of opening diameter, D = 70 mm. It is clear from the figure that, the cup height increases with increasing the die corner radius.

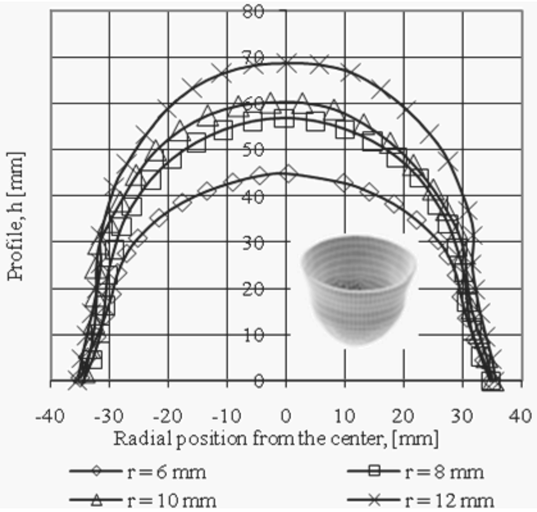


Fig. 2. Sample profile of deformed cup for D = 70 mm

Similar profiles are obtained for other die opening diameters and the relationships between the normalized dome height (h/h_{max}) and the normalized radial position (r/R_D) are depicted in Figure 3. These normalized profiles can be fitted mathematically by the equation:

$$\frac{h}{h_{max}} = -2.3324\left(\frac{r}{R}\right)^4 + 2.7408\left(\frac{r}{R}\right)^3 - 1.4613\left(\frac{r}{R}\right)^2 + 0.0455\left(\frac{r}{R}\right) + 1.0011 \qquad (8)$$

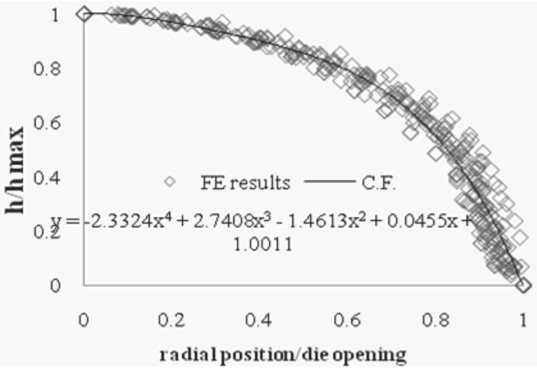


Fig. 3. Normalized cup profiles for free forming

Strain components distributions are plotted versus the normalized radius in Figures 4, 5 and 6 which show typical distributions for the radial, hoop and thickness strain components, for die opening D = 70 mm. The blank holder clearance gap (BHG) is fixed at 0.5 mm and the blank thickness is fixed to 1.0 mm.

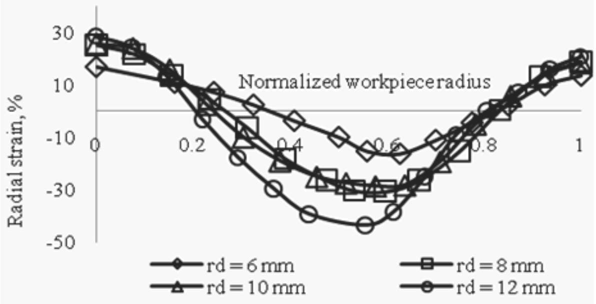


Fig. 4. Radial strain distribution for D = 70 mm

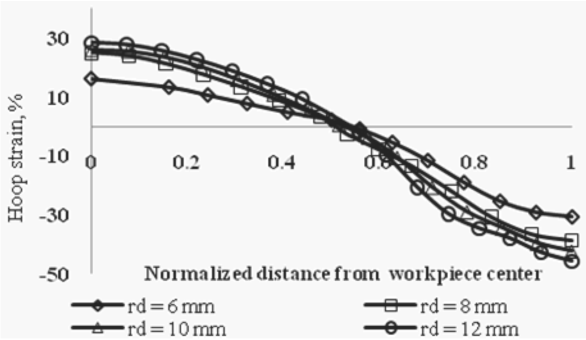


Fig. 5. Hoop strain distribution for D = 70 mm

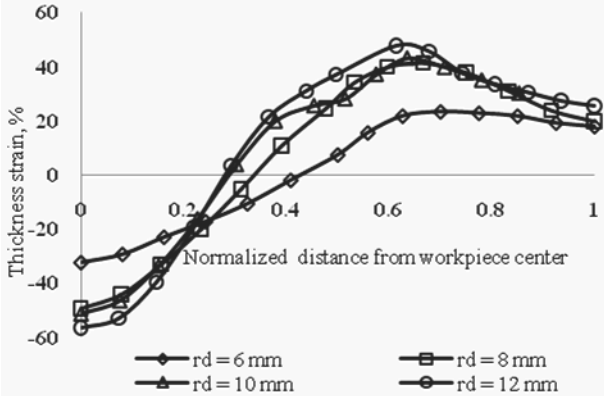


Fig. 6. Thickness strain distribution for D = 70 mm

These figures suggest that the strain components increase with the increase of the die corner radius indicating an overall increase in deformation, which is most noticeable at the cup dome pole. In fact, the cup height increases as the die corner radius increases for all die openings. This is depicted in Figure 7 which shows the effect of die corner radius on maximum cup height for different die opening diameter, D. The height or depth of cup increases with increasing both D and rd. Figure 8 shows the maximum drawing ratio for different die opening diameters, D. It is clear that the maximum drawing ratio β_{max} increases with decreasing of die opening diameter, D and increases with increasing rd.

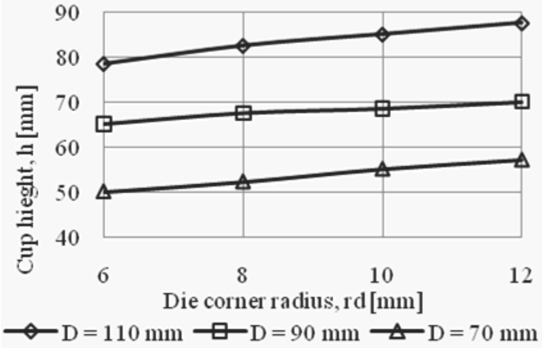


Fig. 7. Effect of die corner radius, rd on cup height

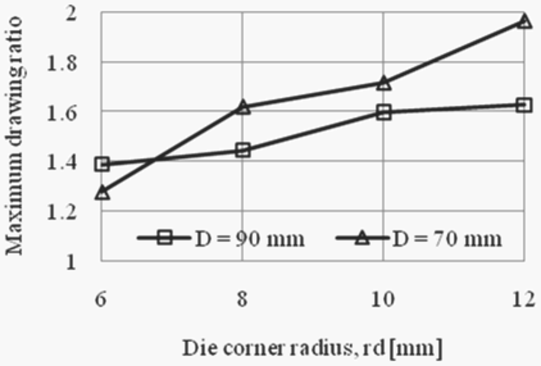


Fig. 8. Maximum drawing ratios at different rd

The energy required to successfully draw a blank of fixed diameter is shown in Figure 9 which also shows the forming pressure applied. Clearly, the energy and pressure increase with the decrease of the die corner radius, rd. The energy is represented here by the HE charge weight.

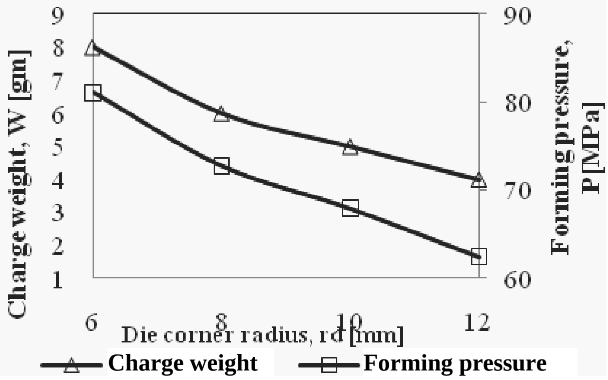


Fig. 9. Effect of die corner radius on charge weight

Figure 10 show some FE images of successful and failed deep drawing runs. The model detects the onset of failure and stop running the solution.

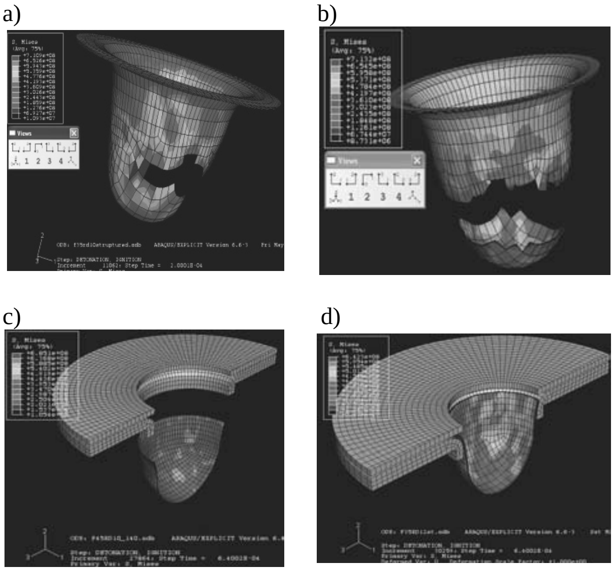


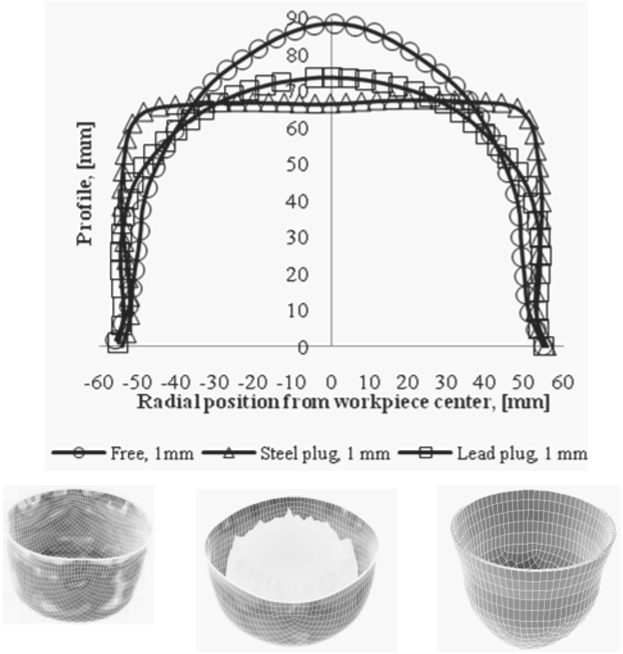
Fig. 10. Some FE plots in different workpiece behaviours: a) Partially torn [D=70 mm], b) Fully torn [D=70 mm], c) Successful [D=90 mm], d) Successful [D=70 mm]

3.2. Plug assisted UNDEX cup forming

A soft (lead) plug and a relatively hard (mild steel) plug of the same mass were considered. It is believed that the use of a relatively hard plug would give better control of the shape of the cup bottom. This finding is clearly depicted in Figure 11 which shows comparison between cup profiles produced using both plugs and the free forming case. Nearly flat cup bottom was noticed in case of using steel assisting plug. Figures 12-14 compare the radial, hoop and thickness strain components of the free forming of circular blank with the cases of using steel and lead assisting plugs. It is noticed that the strain components become more uniform when using assisting plugs with more uniformity for the case with steel plug. This is reflected in the observation in Table 3 which shows the different maximum drawing ratios of the AA 5083-H116 Aluminium alloy. Higher drawing ratios are obtained in cases of using assisting plugs, especially steel plug.

Table 3.
Drawing ratio for different cases of (UNDEX) deep drawing

Case	β_{max}	R mm	Rd mm	Db/2 mm	Δ
Free	1.5	55	8	82.5	0.5
Lead plug	1.63	55	8	90	0.5
Steel plug	1.81	55	8	100	0.5



Steel plug Lead plug Free forming

Fig. 11. Profile of produced circular cups in different cases

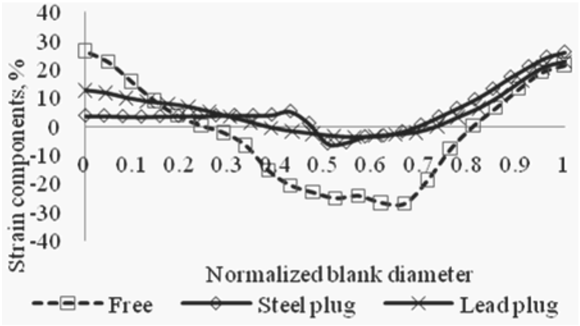


Fig. 12. Comparison of axial strain distributions

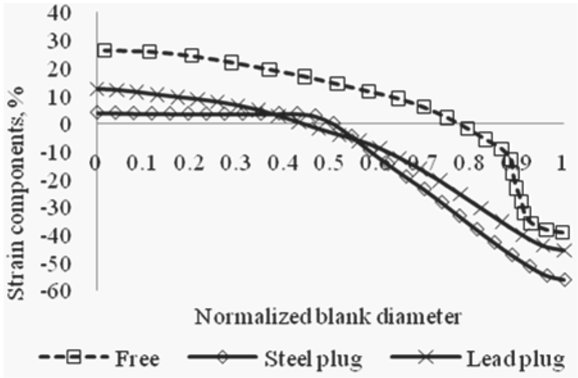


Fig. 13. Comparison of Hoop strain distributions

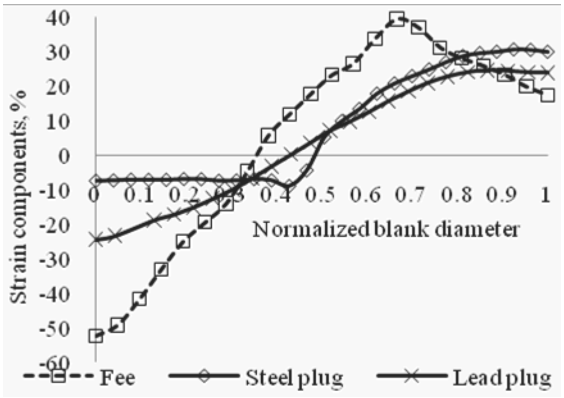


Fig. 14. Comparison of thickness strain distributions

It is worth noting that an assisting plug was introduced to the assembly of the UNDEX cup forming process in order to store some of the energy generated by the explosive charge and deliver it back to the work piece to give a more uniform strain distribution and protect it from getting ruptured under the condition of severe blast loading [6]. However, as depicted in Figure 15 which shows two FE images of drawn cups, using lead and steel plugs, the lead plug itself deforms and imparts its shape to the cup bottom, since lead is a soft material. Thus, in an attempt to control the shape of the cup, it is suggested to use a relatively harder plug with the same mass and subjected to the same amount of energy. As shown in Figure 15, steel plug deforms elastically and acts as a transmitting medium similar to the punch in conventional deep drawing process which enhances the possibility of producing flat bottom cup.

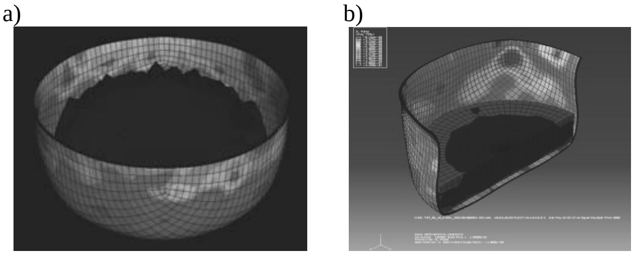


Fig. 15. Deformed shape of drawn cup with a) lead and b) steel plug

4. Conclusions

A 3D finite element model has been developed to simulate the process of the UNDEX cup forming using ABAQUS finite element code. Johnson-Cook (JC) material plasticity model with its damage criterion have been employed to detect the deformation of the sheet metal and onset of damage in the cup forming process with account of strain rate sensitivity. UNDEX free cup forming and plug assisted forming processes have been considered. Both steel (relatively hard) and lead (soft) plugs have been considered and the effects of using these different plug materials on cup profile, strains and the limiting drawing ratios have been elaborated. The present results have revealed that the maximum drawing ratio and uniformity of strain components distribution were both enhanced in the cases of using plug assisted forming in contrast to free forming which supports observation made earlier [6]. The steel assisting plug resulted in nearly flat bottomed cup, with a maximum drawing ratio of 1.8. This result has suggested that using of steel plug in the UNDEX plug assisted cup forming process seems to act as a punch and thus can enhance the ability to control the shape of cup bottom as required. However, this calls for further experimental work to verify this finding. This is intended in a future work to be shown elsewhere.

Nomenclature and symbols

BHG	Blank Holder Gap
EOS	Equation of State
FE	Finite Element
HE	High Explosive
JC	Johnson-Cook plasticity model
JWL	Jones-Wilkins-Lee
UNDEX	Underwater Explosion
A	JC material parameters, static yield stress
B	JC material parameter
C	JC strain rate parameter
D	Die opening diameter
D_b	Blank diameter
E	Young's modulus of elasticity
m	JC heat softening parameter
M_θ	High explosive material constants
n	JC strain hardening exponent
P	Free field pressure loading
P_t	Total pressure
P_o	Peak pressure
R	Stand off distance
r	Radial position
rd	Die corner radius
T	Temperature
T_m	Material melting temperature
T_o	Reference temperature
t	Time
W	Explosive charge mass
α	High explosive material constants
$\beta_{\max}$	Maximum drawing ratio
$\hat{\theta}$	Homologous temperature
θ	Time constant for pressure peak decay
Δ	Blank Holder Gap
$\dot{\varepsilon}$	Strain rate
$\dot{\varepsilon}_o$	Reference strain rate
$\bar{\varepsilon}^{pl}$	Equivalent plastic strain
$\bar{\varepsilon}_D^{pl}$	Equivalent plastic strain at onset of damage
σ_y	Static yield stress
ω_D	State variable represents damage
k_θ	High explosive material constants
γ	High explosive material constants
ρ	Material mass density
υ	Poisson's ratio

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