

Experimental investigation of the effects of blank holder geometry and lubrication on strain distribution in deep drawing

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ABSTRACT

The present paper investigated the key role of blank holder geometry on strain distribution and defect formation during deep drawing of monolithic sheets (aluminum 1060 H14 and brass CuZn10). Four blank holder forms (flat, inclined, concave, and convex) were studied with two different tribological conditions (oil and grease). The experimental study concentrated on the evolution of punch loads, strain paths (radial, hoop, and thickness), and geometrical accuracy. Results indicate that the convex shape is absolutely non-deep drawable (100 % failure) because of its high counter-bending force value. In addition, the concaved holder with decreased wall-thinning by “hydrostatic cushion” was unable to impose a restraining force sufficient to restrict the rim wrinkle. On the other hand, among those geometries, the inclined holder (taper 15°) was found to be a die geometry, which offers better durability and could produce high-hardenability brass with a more stable process than the flat die, illustrating a failure ratio. Strain analysis showed that the ironing effect, caused by the inclined die, is mechanically necessary for generating high hoop tension to obtain defect-free cups. Besides, a wedging effect is observed between viscous lubricants: the grease works as a viscous damper, balancing flow ease with necessary restraint particularly for aluminum.

Keywords: deep drawing, blank holder geometry, lubrication, strain distribution, metal forming.

INTRODUCTION

Sheet metal forming is one of the basic processes in the industry that provides cost-effectiveness and minimum material wastage during large-scale production [1]. In this process, several technologies are involved in which metal forming by drawing method is performed to produce cylindrical, box, and concave shapes. Continuous research and development on forming technologies and tools are essential to cater to the needs of the automobile industry. These tools are required to control the flow of material by forcing the sheet into a die cavity through a punch while pressing the material flat against the die by using a blank holder. Typical products manufactured through the drawing process are beverage cans, artillery shells, bathtubs, cooking pans, and automobile

panels. The holding force applied by the blank holder is now seen to be a critical factor in deep drawing. If it is too small, wrinkling occurs. If it is too large, it prevents the metal from flowing properly toward the die cavity, resulting in stretching and possible tearing of the sheet metal. Determining the proper holding force involves a delicate balance between these opposing factors [2]. In addition to the experimentation, Nimbalkar and Mangshetty [3] performed finite element method simulations where they studied the influence of blank holder inclinations from 0° to 3°. Their investigation exhibited an important trade-off: although the increase of the blank holder angle led to higher punch loads, it largely decreased contact pressure and stress development inside the sheet metal and consequently increased the possibility of producing defect-free

part when extending in sheet metals, while the established work of Younis and Shukur [4] showed the geometrical benefit for inclined blank holders, specifying the 15° inclination as optimal with respect to thickness distribution in their innovation the main influence was slope change. Changing the tooling geometry to control properties of material flow has been the focus of recent studies. Parallel to the investigation of inclined dies, Wang et al. [5] investigated a new curved blank holder instead of the conventional flat blank holder in spherical shape for 5182-O aluminum alloy sheets. They found that limiting drawing ratio (LDR) rose from 1.7 to 2.0 and thickness uniformity improved distinctly with the presence of curvature, and earing defects were effectively suppressed as well. These better properties were explained to be due to the possibility of the curved holder for a more uniform flow of material in various directions. Besheli et al. [6] investigated the effect of material parameters on the defect position by using single and double layer sheet numerical simulations and experimentation. The results show that the maximum plastic strain position depends on yield strength; particularly, regarding to lower yield strength materials like aluminum, the equivalent plastic strain increases sharply around the punch radius producing maximum thinning in this region. On the other hand, they found that significantly higher blank holder force (BHF) is required to control wrinkling in stronger materials. Recently, a study by Béres et al. [7] proposed an extended stress-based forming limit diagram to predict wrinkling in sheet metal forming. The results emphasized that BHF is a key parameter, where increasing BHF enhances normal pressure and suppresses wrinkling, while low BHF promotes instability in the flange region. Addressing the dispersion of process parameters, Palmieri et al. [8] introduced an in-line feedforward control method of BHF to minimize following blank draw-in and estimate friction coefficients on the fly. They found that the dynamic force compensation can effectively suppress defects, but short working interval restricts performance. The delayed adjustment across a certain threshold will result in an irreversible blank sliding and cracking or surface deformation such as galling. Similarly, Guo et al. [9] proposed an intelligent strategy to minimize wrinkling and damage based on deep neural networks combined with a genetic algorithm for multi-defects including failure and wrinkling. They were able to get

defect reductions of (13–18)% through optimization of variable blank holder force trajectories and material flow analysis. Their results also show that there is a need to increase material flow efficiency by the control of force trajectory and die design optimization in order to improve formed quality. In the context of specific geometric modifications, Jabar and Mohammed [10] compared the conventional flat die/blank holder with a 15° sloped counterpart for thickness distribution in aluminum cups. Their results proved that the angular geometry was effective to enhance the metal flow, and then a more homogeneous lesser 10% variation of wall thickness as well as lesser thinning at the critical punch radius region than was obtained with the flat design. These results validate the ability for geometric manipulation to influence material placement and avert basal tearing. Besides force and geometry, Candra and Firmanto [11] also studied the effect of the blank holder gap (BHG) on defect formation in low carbon steel deep drawing. Their combined experimental and numerical results suggested that a BHG which in value was maintained from 100% to 114% of the initial sheet thickness would be best for preventing both wrinkling and cracking, which means advanced control over dimensions as well as force. A study by Klaynil et al. [12] investigated the improvement of the LDR of steel plate cold-rolled commercial using sequential action forming with an inclined blank holder. The results showed that modifying the blank holder geometry and loading sequence improves material flow and reduces defects during deep drawing. The inclined blank holder enhances pressure distribution, leading to higher formability and increased LDR. For complex industrial geometries, Aguado et al. [13] dealt with the challenging trade-off between dimensional precision and defect generation in austenitic steel forming. They found out that when BHF is increased to reduce the bending moment, springback is reduced, but also large necking and surface imperfections occur. The fact that force magnitude is not enough for material behavior regulation emphasizes how complex is the problem when one only relies on geometric optimization approaches. Some of these studies have focused on geometric changes, whereas others considered material-based approaches. A study by Brabie et al. [14] investigated the use of a blank holder plate made from concentric rings to improve deep drawing of mini parts. The

design of the blank holder helped minimize sheet thickness variation and reduce defects. The results highlight that optimized blank holder design is critical for controlling material flow and improving formability. In order to study the effect of lubrication on processing efficiency, Zareh-Desari et al. [15] performed experimental analysis based on modified press drawing oil that was treated with aluminum oxide (Al_2O_3) nanoparticles. They were interested in characterizing the correlation between lubricant composition and forming load. The findings indicated that the enhancement of the tribological behavior of the lubricant contributed to achieving significantly reduced force and higher degree of surface quality for the deep-drawn cups. These findings are consistent with the important role of lubricant selection for reducing friction-induced damaging. Jivan et al. [16] followed the energy-related attitude of deep drawing processes with investigating the tribological behavior of a design solid lubricant system that was prepared as a blend between molybdenum disulfide (MoS_2) and graphite. They examined the rate of decrease in friction and its influence on process mechanics using experimental tribometer tests combined with finite element simulations. It was found that the use of this lubricant mixture reduced the coefficient of friction significantly, which in turn resulted in substantial decrease in both punching force and overall energy consumption. This emphasizes that lubrication strategy is a key enabler for sustainable manufacturing. Radhakrishnan et al. [17] studied the deep drawing capabilities of aluminum sandwich laminates under different lubrications, including Vaseline, grease, and soap. They found that lubrication made a clear contribution to the forming performance, and that with the use of grease, both equivalent plastic strain values and friction were lower than for dry situations. This result demonstrates that viscosity is an important factor to increase material formability and strain distribution, irrespective of the sheet structure. Despite extensive studies on deep drawing, most research has treated blank holder geometry and lubrication as separate parameters, with limited understanding of their combined influence on strain distribution, drawability, and defect mechanisms. In particular, the interaction between non-conventional holder geometries (inclined, concave, and convex) and different tribological conditions (oil and grease) across materials, such as aluminum and

brass remains insufficiently explored. This study bridged this gap through a systematic comparative investigation, providing practical insights for tool design optimization and defect control in deep drawing processes. Thus, the scope was broadened in the present work substantially more than in a comprehensive comparative study. It dealt with blank holder profiles (flat, inclined, concave, and convex) in two materials including aluminum and brass for different lubrications, such as oil and grease. This type of comparative study will give an improved understanding on how blank holder geometry influences the unique strain-hardening properties of aluminum and brass with different lubrication conditions. The contribution of this study is twofold. Scientifically, it establishes a systematic experimental framework to investigate the coupled effects of blank holder geometry and lubrication on multi-directional strain behavior and defect mechanisms. Industrially, it offers practical guidelines for optimizing tool design and selecting appropriate lubrication conditions to minimize defects, enhance process stability, and improve manufacturing efficiency in deep drawing operations.

EXPERIMENTAL WORK

Material characterization

The two typologies of sheet materials used in this study are commercial purity aluminum (1060-H14) and brass (CuZn10). The sheet thickness for both materials was 1.0 mm. Tensile mechanical properties were tested by the uniaxial tensile tests according to ASTM E8. Sections were made at 0° , 45° , and 90° with regard to the rolling direction. Tensile tests were conducted using a universal testing machine (Model: WDW, 100 kN capacity) at a crosshead speed of 2 mm/min. Values of yield strength and ultimate tensile strength were presented in Table 1. Furthermore, the standard chemical composition of used materials is shown in Table 2.

Tooling design and geometry

A new specific deep drawing die-set was designed and manufactured for the purpose of this work. The tooling set up has a punch, a die, and changeable blank holders. The internal diameter of the die (D_{die}) is 42.42 mm, the blank

Table 1. Mechanical properties of Al1060 H14 and CuZn10

Property	Aluminium 1060 H14	Brass CuZn10
Yield stress (MPa)	105.78	141.51
Tensile strength (MPa)	111.61	255.17
Young's modulus (GPa)	69	115
Poisson ratio	0.33	0.34
Elongation (%)	2.61	29.96
Rolling direction 0°	0.74	0.72
Rolling direction 45°	0.195	0.87
Rolling direction 90°	0.40	1
\bar{r} value	0.38	0.865

Note: \bar{r} = normal anisotropy.

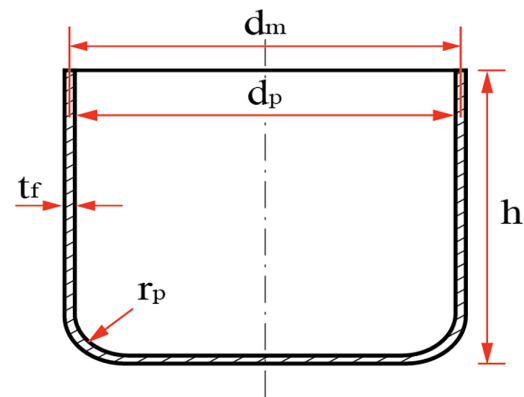


Figure 1. Dimensions schematic of deep-drawn cup ($d_p = 40$ mm, $d_m = 41$ mm, $r_p = r_d = 6$ mm, $h = 30$ mm, and $t = 1$ mm)

diameter (D) is 80 mm, and the clearance between punch and die (c) is 1.21 mm for each side. The c was chosen based on the relation between the c and blank thickness (t). In this study, the clearance ($\approx 1.1-1.25 t$) was adopted based on Singh and Agnihotri [18]. The die edge radius (r_d) and the punch edge radius (r_p) are 6 mm, and the punch diameter (d_p) is 40 mm, giving a mid-thickness diameter (d_m) of 41 mm, as indicated in Figure 1. Finally, Figure 1. shows schematically the geometrical dimensions of the target deep drawn component product for a planned cup height (h) of 30 mm theoretically calculated, which corresponds to the minimum usable depth after trimming.

The effect of the boundary conditions is studied by imposing four different blank holder geometries, which are reported in Figure 2 and described as follows:

1. Flat holder (type a): It has regular flat-based geometry, and 0° contact angle which is considered as the reference base pool.
2. Inclined holder (type b): It is employing the taper angle ($\alpha = 15^\circ$) to be wedge.
3. Concave holder (type c): It has an outward curvature radius ($R_c = 10$ mm) of blank holder.
4. Convex holder (type d): It has the recess inside with $R_c = 10$ mm, which applies a reverse bending to the blank prior to entering die.

Theoretical drawability

To establish a rigorous mechanical basis for the observed deformation behavior, the experimental drawing parameters were evaluated against the theoretical formability limits of the investigated materials. This analysis aimed to quantify the severity of the drawing process and correlate the anisotropy of the material with the successfully achieved draw ratios. Accordingly, the required drawing criteria were calculated using the standard theoretical relationships established in the literature. Drawing parameters: The mid-thickness draw piece diameter is $d_m = 41$ mm (punch = 40 mm + thickness = 1 mm). Given the blank diameter $D = 80$ mm, the total coefficient of deep drawing is $m = d_m/D = 0.5125$, resulting in a relative strain of drawing reduction = 48.75%. The applied experimental draw ratio ($DR = D/d_m$) is 1.95. Anisotropy: The calculated Lankford coefficients (normal anisotropy \bar{r}) are 0.38 for aluminum 1060 H14 and 0.865 for brass. Theoretical limiting drawing ratio (LDR) for conventional processes can be calculated using Equation 1 [19]. The theoretical LDR is 1.86 for aluminum and 2.06 for brass. It is evident that the applied experimental ratio of aluminum (1.95) significantly exceeds

Table 2. Chemical composition of Al1060 H14 and CuZn10 (standard)

Material	Al	Cu	Zn	Fe	Mg	Mn	Si	Ti	Ni	Sn	Pb
Aluminium 1060	99.60	0.05	0.05	0.35	0.03	0.03	0.25	0.03	-	-	-
Brass CuZn10	0.02	89–91	Rem	0.05	-	-	-	-	0.3	0.1	0.05

Note: Rem = remainder (zinc).

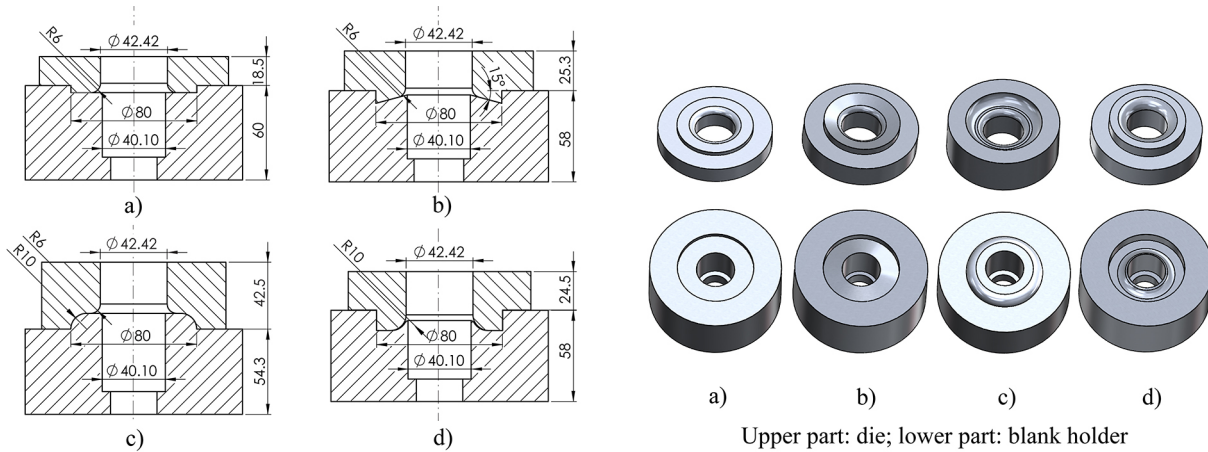


Figure 2. 3D models of designed blank holder geometries: a) flat, b) inclined with 15° angle, c) concave, d) convex

the theoretical LDR (1.86), while the ratio was within the theoretical limit for brass.

$$\ln(LDR) = \eta \sqrt{(\bar{r} + 1)/2} \quad (1)$$

where: η – deformation efficiency and equal to 0.75, \bar{r} – normal anisotropy

Strain measurement

Deep drawing tests were conducted on a universal testing machine (model WDW, 100 kN capacity) with a special tool as illustrated in Figure 3. The forming was carried out at a constant punch speed of 50 mm/min. In order to check the influence of friction, two different lubrication states were implemented, such as engine oil (15W-40), grease (lithium mp-3), the specifications of which are detailed in Table 3. Drawing continued either until a drawn cup was completely formed or the part broke.

In order to analyze the distribution of strain, an 8-concentric-circle grid pattern was mechanically scribed on the blank surface by a high-precision template and a hardened material scribe pen. Circles varied in size from starting at 10 mm in diameter in the center to 80 mm on an edge, as shown in Figure 4.

The instantaneous positions of the deformed grid lines were directly measured along the axial from the center to the wall edge of the cup to find the radial deformation. Measurements were further taken for the same areas to specify wall thickness in a way that required high precision; this was done by utilizing a digital micrometer (accuracy 0.001 mm). From these

measurements, the true strain components were determined as follows:

- The radial strain (E_r) was determined using Equation 2.

$$E_r = \ln\left(\frac{R_f}{R}\right) \quad (2)$$

where: R_f – final radius of deformed circle after forming, R – initial radius of grid circles

- The thickness strain (E_θ) was calculated using Equation 3.

$$E_\theta = \ln\left(\frac{t_f}{t}\right) \quad (3)$$

where: t_f – ultimate wall thickness, checked after forming, t – initial sheet thickness.

- If the material follows the volume constancy law, theoretically the hoop strain (E_z) was derived using Equation 4.

$$E_z = -(E_r + E_\theta) \quad (4)$$

- In order to sum up the integrated plastic deformation at each imaginary grid point, the effective strain was obtained. This scalar sum consists of the three major principal strain components (radial, thickness, and hoop) according to the Von Mises criterion, which can be used as a single value for evaluating the magnitude of deformation. The effective strain (E_{eff}) can be calculated using Equation 5.

$$|E_{eff}| = \sqrt{\frac{2}{3}(E_r^2 + E_\theta^2 + E_z^2)} \quad (5)$$

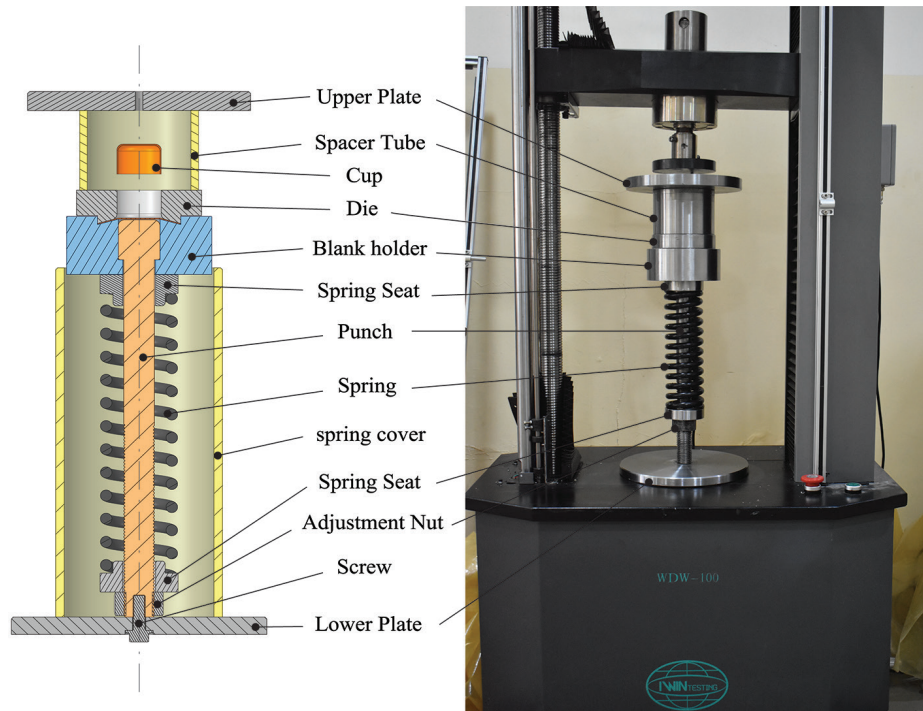


Figure 3. Deep drawing process experimental set up: a) cross sectional view of internal assembly highlighting component names, b) tooling jig mounted on WDW-100 kN machine

Table 3. Lubrication characteristics and specifications

Lubricant type	Commercial name	Base type	Grade / Viscosity	Operating temp. range
Grease	Lithium MP-3	Lithium-based	NLGI Grade 3	-20 °C to +130 °C
Oil	MANNOL TS-1 SHPD	Multigrade engine oil	SAE 15W-40 (ACEA E7, API CH-4/SL)	-20 °C to +40 °C

Experimental conditions

To ensure a clear understanding of the experimental campaign, all studied variables, including blank holder geometries (flat, inclined, concave, and convex), material types, and lubrication conditions, are summarized in Table 4. For each

experimental case, the deep drawing process was repeated three times (Trials A, B, and C) to ensure the reliability and repeatability of the results, covering a total of 48 samples (Tests 1–48). This comprehensive matrix provides a systematic reference for the different test cases before discussing the results in Figure 5.

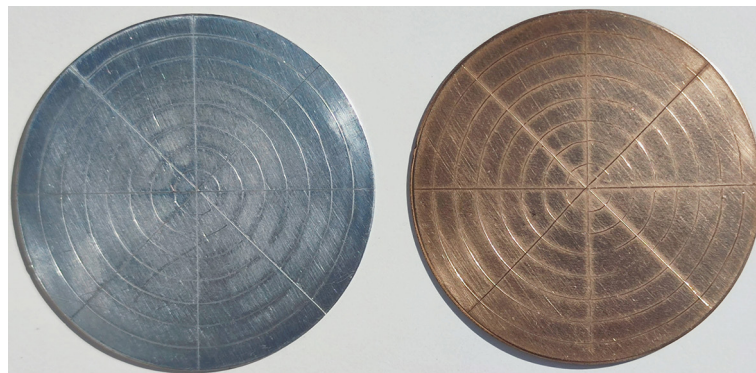


Figure 4. Blank with scribed concentric circles for strain measurements

Table 4. Experimental matrix of blank holder geometries, materials, and lubricants

Flat blank holder						Concave blank holder					
AL			Brass			AL			Brass		
Case 1	Oil	Grease	Case 2	Oil	Grease	Case 5	Oil	Grease	Case 6	Oil	Grease
A	1	4	A	7	10	A	25	28	A	31	34
B	2	5	B	8	11	B	26	29	B	32	35
C	3	6	C	9	12	C	27	30	C	33	36
Inclined blank holder						Convex blank holder					
AL			Brass			AL			Brass		
Case 3	Oil	Grease	Case 4	Oil	Grease	Case 7	Oil	Grease	Case 8	Oil	Grease
A	13	16	A	19	22	A	37	40	A	43	46
B	14	17	B	20	23	B	38	41	B	44	47
C	15	18	C	21	24	C	39	42	C	45	48

Note: A, B, and C represent the three experimental trials for each case.

RESULTS AND DISCUSSION

Analysis of failed specimens

The number of failures per each blank holder geometries is summarized in Figure 5. Six experimental trials under two types of lubricated conditions (oil and grease) were repeated for the two materials including aluminum and brass. The data demonstrates an apparent geometric effect wherein failure rate in the convex holder consistently was the highest for each material (recording 6 failure cases), which means 100% failure rate equivalent. This high failure ratio leads to elimination of the convex geometry from the comparative charts that follow. Next in line was the concave holder (6 brass and 4 aluminum). On the other hand, the inclined holder performed

better with all samples (0 failures) of both aluminum and brass, turning out well (100% success). In comparison, the flat holder performed less consistently with 1 failure and 2 failures in brass and aluminum respectively.

Punch load evolution: geometric and tribological effects

The peak punch load evolution that is analyzed in Figure 6 reveals the importance of geometric constraint and tribological state. For aluminum, under oil lubrication condition (Figure 6a), the data indicate that the concave holder acts as a “geometric brake” impeding material flow in more comparison with flat holders. The inclined holder gives the lowest load and friction, proving that a taper indeed promotes flow and

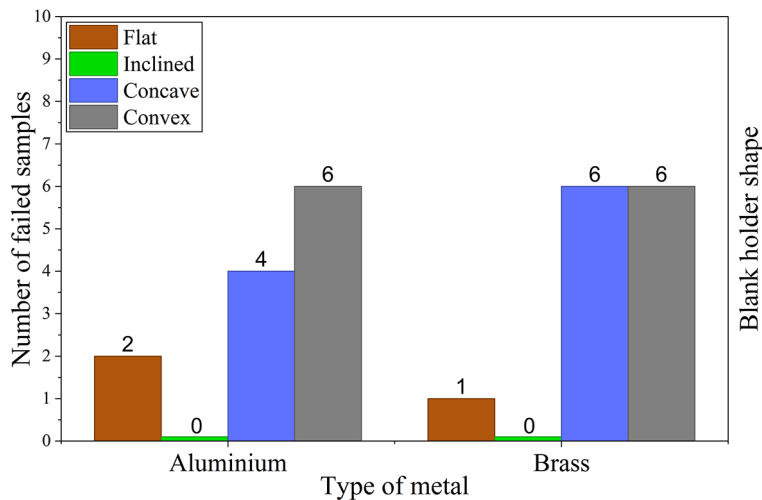


Figure 5. Failed samples number for each of the four blank holder shapes

eliminates friction. However, under grease lubrication (Figure 6b), a change in behavior is seen at which the Inclined holder load increases slightly compared to the flat holder. This behavior is caused by the viscous grease confined between inclined surfaces, causing a hydrostatic wedging effect and localized pressure, as opposed to a flat holder providing a passage for grease escape. When the charts from aluminum are compared with those obtained for brass, a metal that has larger deformation work values, the same trend is observed, even though higher loads are involved. The concave sweep always provides the highest resistance in both regimes. Specifically, under oil lubrication (Figure 6a), the concave holder had the highest loading, and then there was an abrupt stoppage. This increase is ascribed to severe flange wrinkling; the wrinkle accumulation increased resistance at the die entry and resulted in an early termination to avoid cup jamming into the die cavity. Next is the flat holder, and lastly the inclined holder (lightest load). Under grease lubrication (Figure 6b), the concave holder also presented the maximum load with a sharp decline taking place at 32.5 mm of deflection

and a second increase. This is an uneven phenomenon caused by cup misalignment created by the instability of the concave shape. Next is the inclined holder, and lastly the flat holder (least load). The low load in the flat holder had to be due to less resistance of grease movement between opposing surfaces and passing of slide through inclined holder imposed the slide with a mild hydrostatic constriction which increased the load. In this sense, the inclined geometry is able to supply a “controlled restraint” enough to suppress wrinkles, preventing catastrophic jamming as seen in the concave one with process stability.

Strain distribution analysis

From the strain distribution analysis, the deformation behavior of material and the stretching severity that it experiences during deep drawing process are quantitatively evaluated.

Radial strain evolution

The distribution of the radial strain (ϵ_r) along a curvilinear path from the center of the

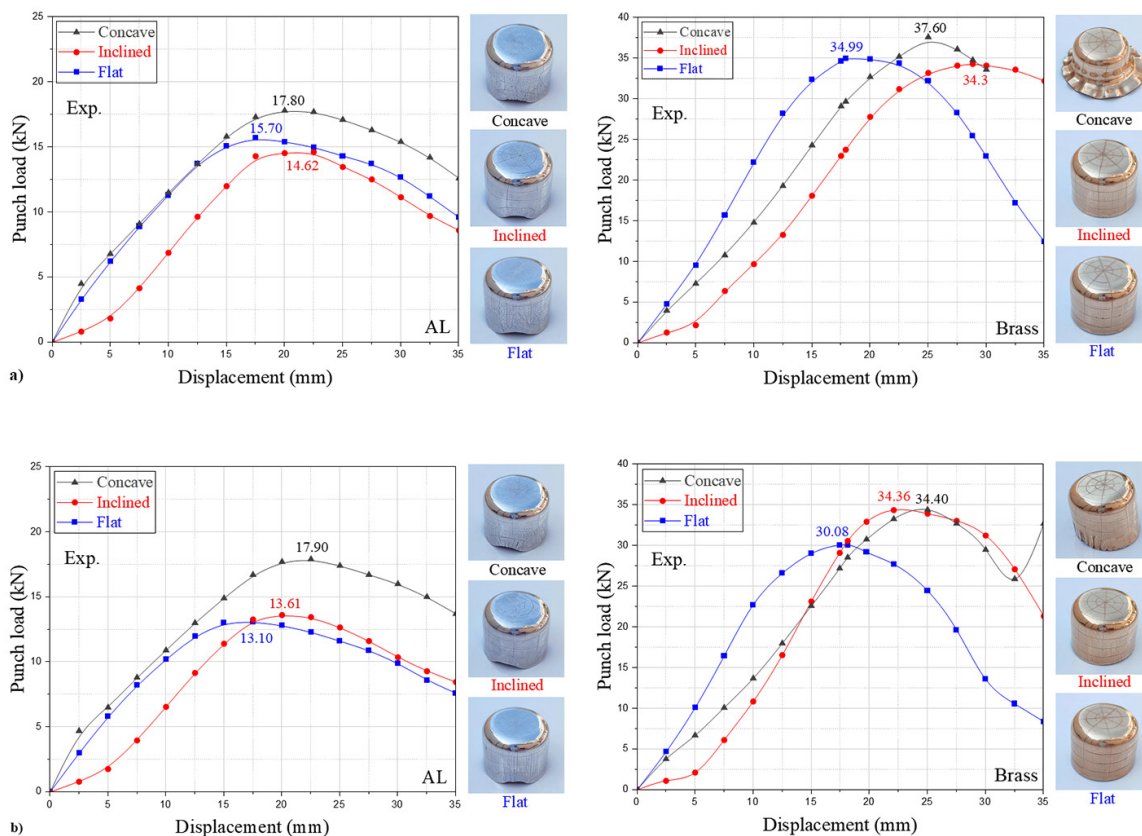


Figure 6. Effect of blank holder geometry on punch load evolution for aluminum and brass: a) under oil lubrication, b) under grease lubrication

cup to the flange edge was analyzed (Figure 7) to explain the deformation severity imposed by blank holder geometry under lubricated condition. For aluminum, the strain profile under oil lubrication (Figure 7a) demonstrates that the concave holder generates a sharp localized strain peak around the punch radius zone (around 15–20 mm), suggestive of highly severe tensile stretching caused by geometrical lock-up. In contrast, an inclined profile shows better flow properties and decreases radial strain values in a cup wall region with respect to flat one. This effect is even more pronounced in the case of grease lubrication (Figure 7b) in which at the flange extremity, the inclined holder does bear much less radial strain than that on the flat holder. This decrease indicates that the tapered gap efficiently accommodates the viscous lubricant, thus decreasing the radial tension needed to pull in material. Under grease lubrication (Figure 7b), the concave blank holder showed an anomalous and distinct behavior, recording the lowest strain values in the mid-wall region; this is attributed to the ‘hydrostatic cushioning effect,’ where the

concave section acts as a reservoir trapping the high-viscosity grease. In contrast, the inclined blank holder displays an intermediate behavior characterized by instability caused by the ‘wedging effect’. Transitioning to brass (Figure 7), the elevated flow stress of the material points to the limitations of confining geometries. The concave holder showed early failure under oil (Figure 7a) and grease (Figure 7b) conditions, resulting in immediate fracture, preventing any strain data collection. On the other hand, inclined design remained effective in reducing excessive radial stretch. Under oil lubrication (Figure 7a), inclined geometry showed a more uniform and stable strain distribution, which prevented the sharp localized gradients seen on the flat profile. Similarly, under grease lubrication (Figure 7b), the inclined holder still had an advantage over the flat holder in obtaining a smoother strain gradient towards the flange edge. Therefore, the inclined geometry is confirmed as the best design to reduce radial stretching, avoid excessive thinning around punch radius and achieve a uniform flow.

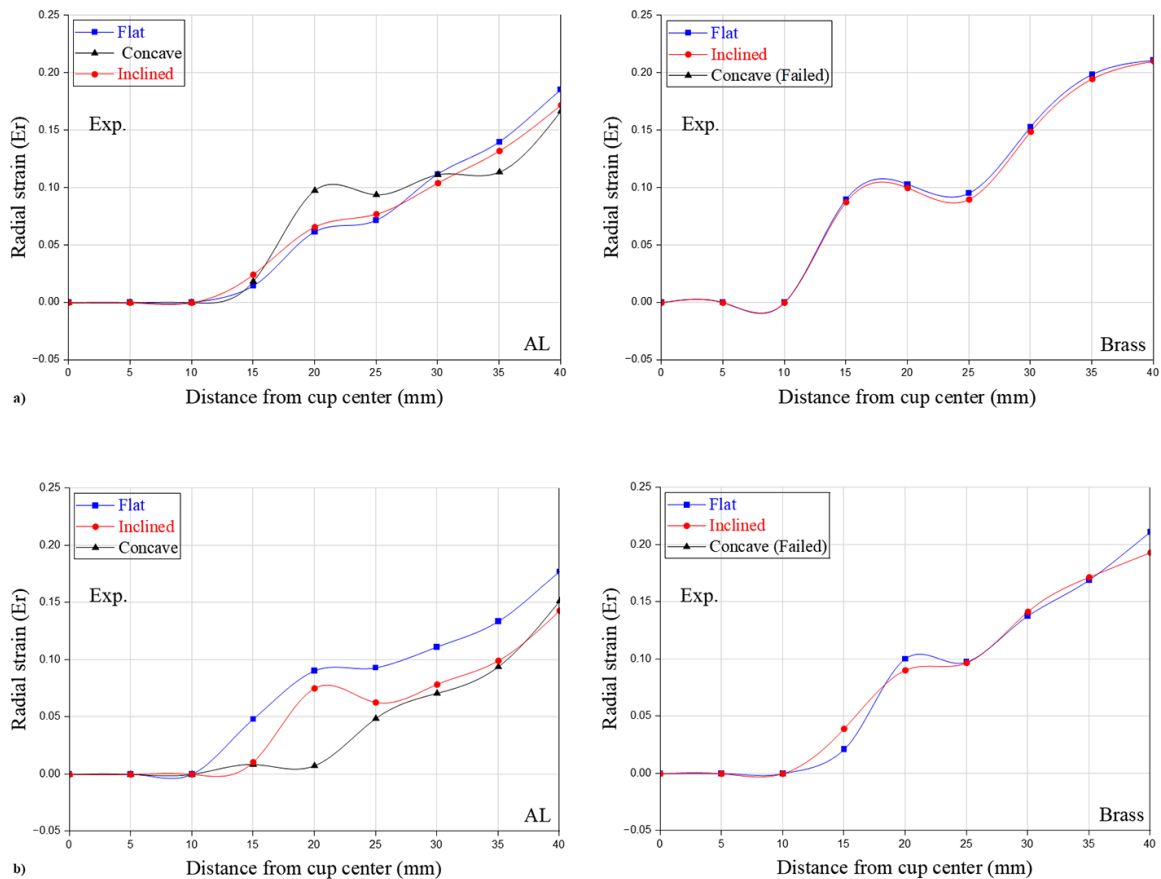


Figure 7. Radial strain distribution for aluminum and brass: a) under oil lubrication, b) under grease lubrication

Thickness strain evolution

The evolution of thickness strain (E_{θ}) highlights the complex interplay between holder geometry, lubricant viscosity, and material flow stress. For aluminum, under oil lubrication (Figure 8a), the inclined holder exhibited the most severe thinning at the punch radius, indicating intense meridional stretching used to suppress flange thickening. Meanwhile, the flat holder displayed a strain profile comparable to the concave geometry at the punch radius, with both exhibiting reduced thinning. However, the concave holder was uniquely characterized by excessive thickening at the cup edge. This is attributed to a pre-forming effect where the geometry initially bends and feeds material inward reducing tension at the radius but, subsequently causes material accumulation at the die entrance. Under grease lubrication (Figure 8b), the trend shifted significantly: the flat holder suffered the most severe thinning, followed by the inclined, while the concave holder recorded the least thinning. The improvement in the inclined and concave geometries is attributed

to the high viscosity of the grease, which reduced friction, combined with the mechanical advantage of the tapered surfaces. Specifically for the inclined geometry, the drawing force decomposes into a normal component compressing the material and a parallel component facilitating smooth influx into the die. Transitioning to brass (Figure 8), the concave geometry failed under all conditions, where restrictive wrinkling rapidly progressed into tearing. Comparing the remaining geometries: under oil lubrication (Figure 8a), the inclined holder outperformed the flat profile, showing less thinning due to smoother flow. However, under grease lubrication (Figure 8b), a distinct tribological reversal occurred: the inclined holder exhibited more thinning than the flat holder. This phenomenon is explained by the viscous drag effect. Unlike the ductile aluminum, the stiff brass material could not accommodate the thick viscous film within the narrowing tapered gap. Instead, the grease created high hydrostatic resistance that impeded the flange sliding, forcing the cup wall to undergo excessive stretching to compensate for the punch displacement.

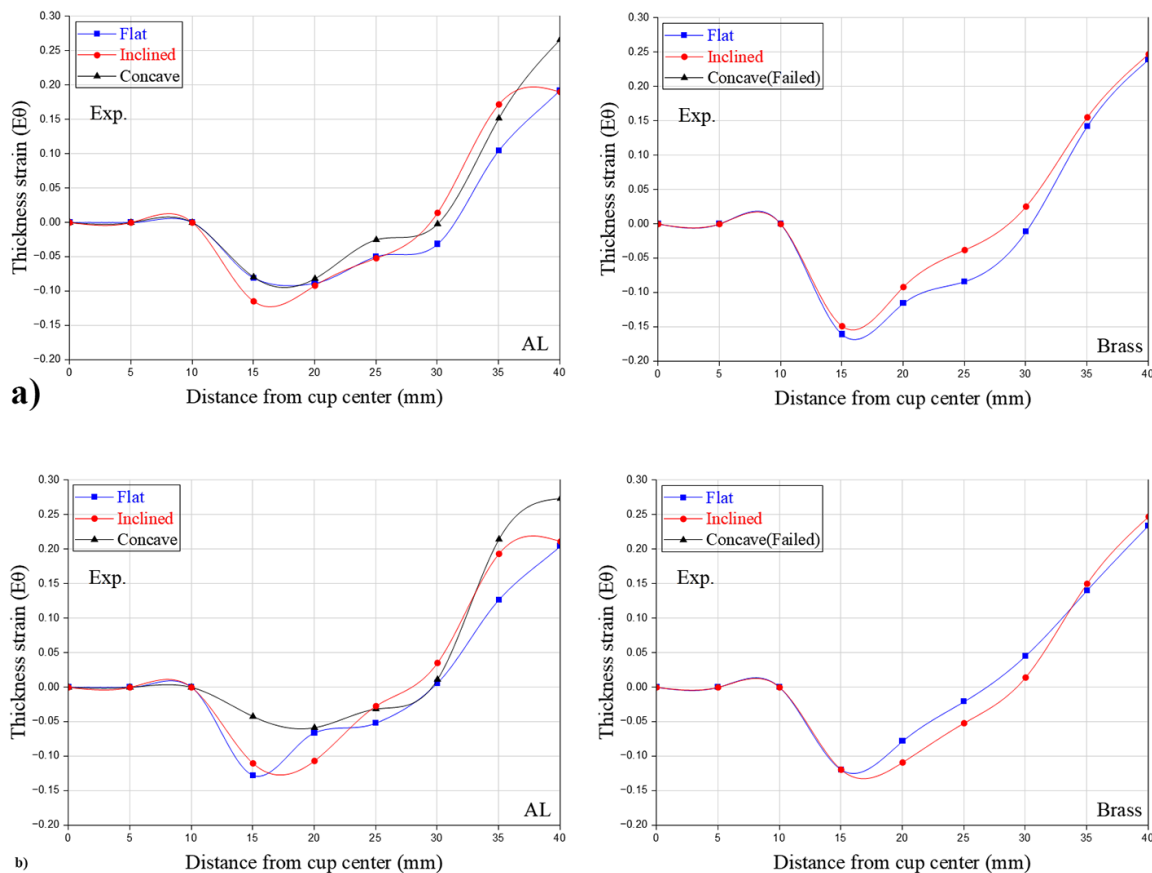


Figure 8. Thickness strain distribution for aluminum and brass: a) under oil lubrication, b) under grease lubrication

Hoop strain evolution

The development of the hoop strain (ϵ_z) demonstrates circumferential behavior, the stability and resistance to wrinkling of which are relevant. Strain profiles show similar geometrical effects for the aluminum regardless of lubrication conditions. Under oil lubrication (Figure 9a), at the punch radius of 15 mm, the inclination holder presents the largest positive peak, then the flat holder, and the concave holder. This hierarchy reflects a better fit to the punch geometry for the inclined holder, as induced by effective meridional tension. As of the deformation at 40 mm flanging-depth, the concave holder presents as an outlier in a more unambiguous sense, and shows a relatively sharp drop towards the highest compression value (farther away from zero and -0.44). The flat holder exhibits a higher flow rate, and the inclined one gives the lowest negative values (nearest zero), meaning an optimal circumferential decrease is achieved. Under grease lubrication (Figure 9b), this tendency is strictly reinforced, and one sees for the inclined geometry a continuous variation

in strain values due to the tapered nature of its gap, which does not impose any “geometrical choking” as it was observed for the concave profile. Transitioning to brass (Figure 9), the concave geometry failed due to restrictive wrinkling, preventing successful forming. Comparing the feasible geometries on oil lubrication (Figure 9a), the flat holder presents a slightly higher positive peak at the punch radius than that of the inclined holder. However, under grease lubrication (Figure 9b) a well-defined, yet nontrivial behavior develops. The flat holder has a “wavy” profile of oscillation: peaking at 15-mm, dipping at 20 mm, and then resurging. This is the instability of flow (stick-slip). The inclined holder, in contrast, exhibits a lower, but much smoother and more stable curve. The lower peak in the tilted profile at a distance of R from the punch center is due to what the authors call here the viscous drag effect: The hydrostatic resistance exerted by grease in that region reduces perturbation and sudden reliefs (which are visible for the flat specimen), providing a controlled deforming section.

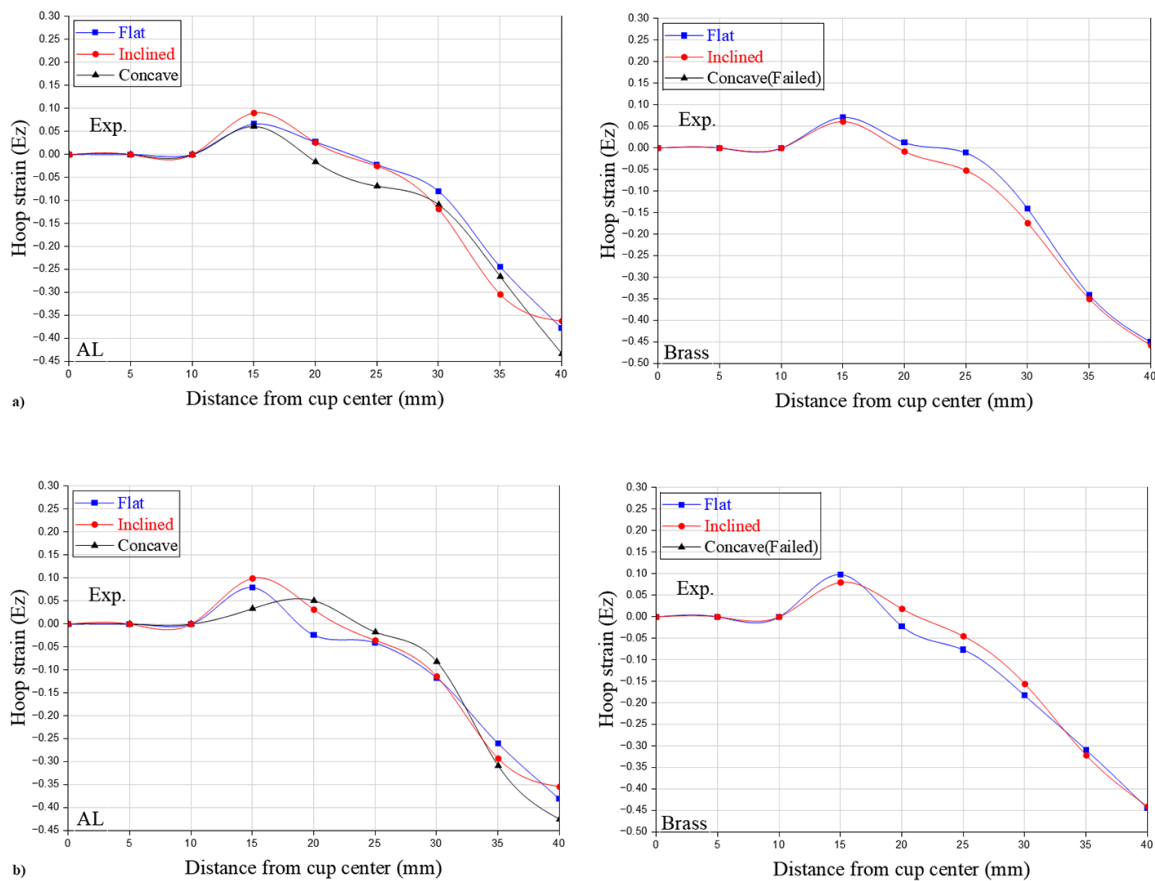


Figure 9. Hoop strain distribution for aluminum and brass: a) under oil lubrication, b) under grease lubrication

Effective strain distribution

Effective strain (E_{eff}) stands for the accumulated amount of plastic deformation which combines radial, thickness, and hoop strains to be a scalar parameter. The parameter therefore provides a general measure of the degree of work hardening and the geometric fit obtained during forming. For oil lubricated aluminum (Figure 10a), the distribution exhibits characteristic mechanical features. Note that the inclined holder has the largest maximum value at the punch radius (~ 15 mm), which supported our earlier results of “intense meridional stretching” to guarantee very good conformity with respect to punch shape. In turn, the lowest tensional value is recorded at the radius in the case of a concave holder and rapidly increases to reach its maximum value at the flange end. This discrepancy validates the “pre-forming vs. choking” mechanism, that is, because of the initial bending, small work deformation occurs in early stage and that is why there is high accumulation at flange. Under grease lubrication (Figure

10b), the concave holder retained this non-uniform distribution. The flat holder on the other hand shows a clear time-varying behavior (it first goes higher than the inclined one, then it reduces downward and finally upward at edge of the cup). In contrast, the inclined holder presents quite a gradual and steady transformation, evidence of tensile work homogeneously distributed by the hydrostatic grease cushion that effectively prevented unstable strain concentrations. When transitioning to brass (Figure 10), one could make a close comparison. Under oil lubrication (Figure 10a), a clear “crossover” phenomenon is observed, as shown: the flat holder experiences leading effective strain at the punch radius owing to sudden bending, while the inclined holder surpasses it at the flange extremity due to extra plastic-strain energy (meridional stretching) consumption to resist thickening. Finally, under grease lubrication (Figure 10b), the flat holder makes a slightly higher peak intensity than the inclined holder at the punch radius. These concords well with

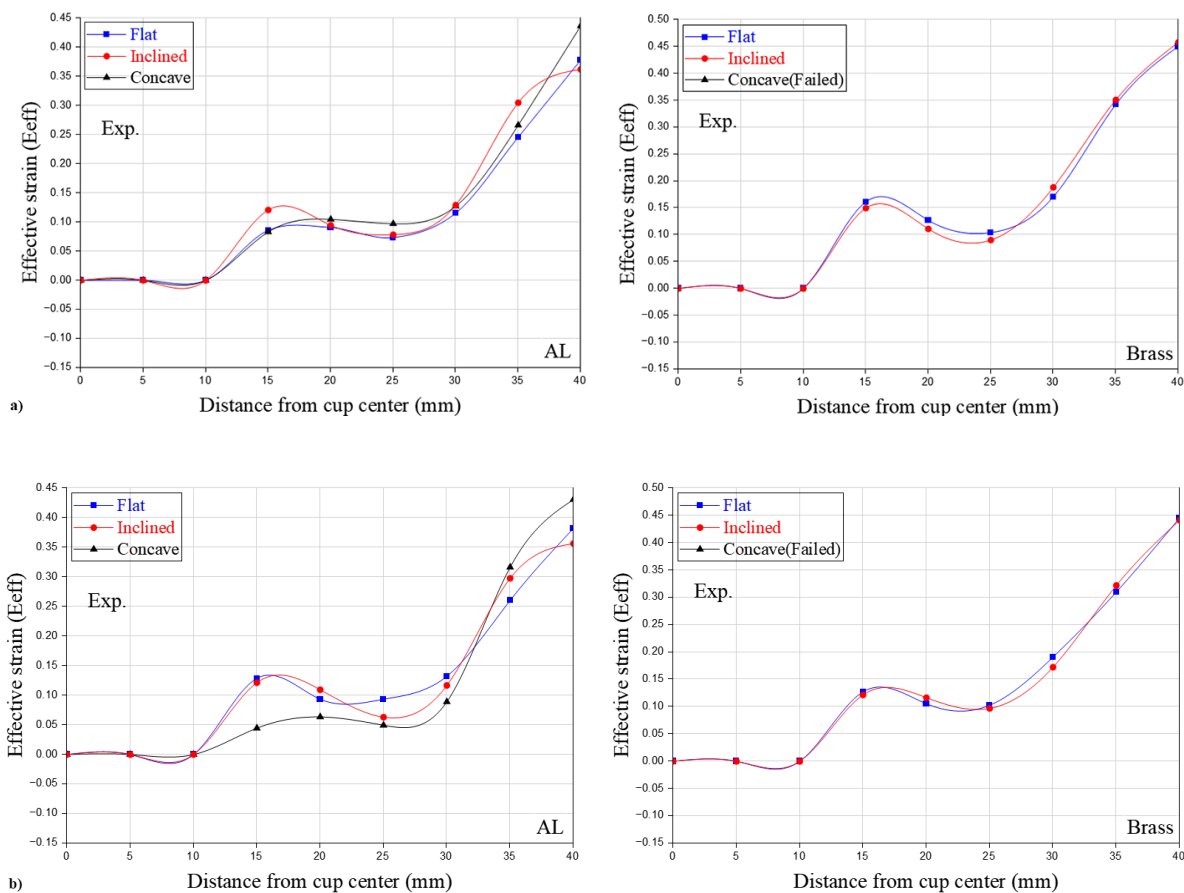


Figure 10. Effective strain distribution for aluminum and brass: a) under oil lubrication, b) under grease lubrication

the observed viscous drag behavior; in which the yielding of the grease layer around a slope acts to damp its progress, leading to localized less severe deformation, as compared to the undamped flat profile.

Finally, and based on the results presented above, the experimental performance of the flat blank holder underscores a critical and complex interaction between tool geometry, lubrication properties, and the applied blank holder force (BHF). Regarding Aluminum 1060, the high failure rate, specifically the basal tearing observed under oil lubrication, aligns with the theoretical limits established in Theoretical drawability. This failure is directly attributed to the low limiting drawing ratio (LDR) and restricted ductility of the material, which, when coupled with the high friction of low-viscosity oil and inadequate BHF adjustment for such conditions, severely impeded material flow into the die. Conversely, the 100% success rate of Aluminum with grease lubrication demonstrates how a high-viscosity medium can compensate for these inherent geometric and material limitations by facilitating a more uniform flow.

In the case of brass, despite its superior theoretical drawability calculated in Theoretical drawability, the isolated failure under grease lubrication was characterized by wrinkling, rather than tearing. This phenomenon occurred because the high-viscosity grease reduced friction excessively, leading to an uncontrolled and accelerated metal flow into the die cavity that the flat geometry could not stabilize, even with blank holder force application. These results confirm that conventional flat blank holders are highly sensitive to the tribological balance; any deviation leads to either tearing (due to excessive friction) or wrinkling (due to excessive flow).

These observations are strongly supported by the findings of Zareh-Desari et al. [15] and

Radhakrishnan et al. [17], who identified lubrication viscosity as a primary determinant in managing the trade-off between friction and material flow efficiency. Furthermore, when comparing these results with the works of Klaynil et al. [12] and Jabar and Mohammed [10], it becomes evident that the proposed inclined blank holder offers a significantly broader ‘processing window.’ It is worth noting that while previous literature has extensively explored flat and inclined geometries, there is a lack of comparative data regarding concave and convex profiles in deep drawing. Therefore, this study bridges a significant gap by introducing these complex curvatures. By optimizing pressure distribution and streamlining material flow, the inclined geometry achieved a 100% success rate across all tested conditions, effectively overcoming the inherent sensitivities to lubrication type and blank holder force that limit the industrial reliability of conventional flat designs.

Deep drawing defects

Forming defects are the ultimate judge of failure in deep drawing as a result of incompatibility of process variables (blank holder geometry, lubrication, and materials properties). In the present experiments, five main types of defects have been detected and studied with regard to their influence on the final geometry and surface quality.

Wrinkling

This defect manifests itself in the form of waviness on the flange faces or the upper cup wall as seen from Figure 11 for aluminum and for brass. This is because of the compressive circumferential stress that occurs in the blank flange as its diameter reduces. Wrinkling was associated



Figure 11. Wrinkling defect

with insufficient restraint in the present work; the concave blank holder was not able to restrain the metal from buckling under tangential stress, and caused material buildup.

Tearing

This defect is characterized by complete process collapse, which occurs at the cylinder wall bottom region, near to the punch profile radius (see Figure 12). If the radial tensile stress is too large, then tearing may happen, when the radial tensile stress exceeds the ultimate tensile strength of material in critical thinning zone. In the conducted testing, this was caused by excessive restraint due to extremely high friction that governed the deformation process of high frictional forces limited metal flow and forced the wall to extend until failure.

Earing

This failure is seen just to the peak and valley undulations from the top rim of the cup in Figure 13. This fault is not the result of tooling damage, but it is due to planar anisotropy in the sheet. The metal flow properties vary relative to the rolling direction, leading to uneven flow that forms an “earing” pattern.

Puckering

This defect is the waviness on the side wall of the cup, not on flange as generally occurs around unsupported area during drawing (refer to Figure 14). Puckering is induced in the area, which lies unsupported between the punch radius and the die radius. The material experiences some tangential compressive stressing with little support from either the die or punch walls, which leads to local buckling of the wall prior to completion of drawing.

Uneven phenomena

This defect appears as an obvious geometric asymmetry in the material distribution around the circumference of the cup, although potentially characterized by differences compared to normal in wall height or flange length once again for component shown in Figure 15. This is mainly a result of misalignment between the blank and tool. In the experiments that are described here, this failure manifested itself in a specific manner through concave blank holder geometry. The holder had a raised protrusion and did not have any locating recess or pocket in which to insert the blank. This made accurate blank centering, difficult and uncertain as against other holders having suitable recesses for a positive centering of the blank.



Figure 12. Tearing defect



Figure 13. Earing defect



Figure 14. Puckering defect



Figure 15. Uneven phenomena

CONCLUSIONS

The conclusions are drawn from the experimental results of aluminum and brass in deep drawing process with diverse blank holder shapes and lubrication conditions as follows:

- The inclined geometry of the blank holder resulted in a more successful process.
- Deep drawing is fully failed with the convex blank holder and this leads to register a failure rate of 100%.
- The concave holder resists thinning by means of “hydrostatics cushioning”, but wrinkling and eccentric slipping occurred. In contrast, the tilted holder created averagely necessary ironing for making accurate cups without defects.
- Radial strain: The inclined blank holder guarantees the smoothest material flow, forcing out all of frictional drag driven localized tensile peaks with a flat holder and geometric constraints with a concave holder.
- Thickness strain and final thickness: The concave holder is beneficial in minimizing wall thinning, but does not mitigate rim wrinkling. On the other hand, the slanted holder achieves better dimensional accuracy by controlling wall thinning “ironing effect” and eliminating material accumulation at the rim.
- Hoop strain: The inclined blank holder provides a circumferential restraint force that is effective in preventing slack of material like seen in the concave geometry and an unlike flat holder where the tensile quantitatively are poorly distributed.
- Effective strain: The inclined holder achieves the most homogeneous strain distribution. It optimally balances wall strength and rim stress, avoiding the wrinkling (concave holder) and tearing (flat holder) extremes.
- With oil, the inclined holder was the most successful sample and required less force compared to flat. In contrast, the flat holder was least successful with grease only, the concave holder had maximum restriction and convex caused an instantaneous break.
- Grease is the best medium to reduce friction for aluminum in a flat holder, its high viscosity prevents it from doing that well for brass. It can do that with both metals and prevent the high friction we have with aluminum, but only in the inclined holder by the means of ‘wedging effect’; it is also thus a cushion.
- Oil gives the best surface finish, especially with brass in the inclined holder. On the other hand, it produced enormous resistance for aluminum in a flat holder. Indeed, when

aesthetics after forming are of top priority, it is still the best option.

- The best forming combination for aluminum is observed when using the inclined holder with grease lubrication, while for brass it is observed when utilizing the inclined holder with oil lubrication.

Finally, this study provided a comprehensive evaluation of unconventional blank holder geometries specifically introducing newly investigated concave and convex profiles alongside the 15° inclined and traditional flat types under severe drawing conditions. The novelty of this work lies in the systematic exploration of these non-traditional geometries, which expands the existing literature beyond the simple angular modifications studied by previous authors. The experimental results demonstrated that the inclined holder is the optimum choice for successful forming, while the investigation of concave and convex holders provides significant scientific value by defining the critical formability limits and mechanical constraints of such designs. This broader geometric scope offers a more complete understanding of material flow control, effectively bridging the gap in current sheet metal forming research.

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