Review of Recent Development in Deep Drawing Process

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ABSTRACT

Deep drawing is a common metal forming process used to manufacture recessed three-dimensional parts from flat sheet metals. The research in deep drawing has been generic over the last few decades and various aspects of this process have been investigated. The paper aims to review the following aspects of deep drawing process that affect the quality of the product, tooling life and process design:

i. The development of a theoretical model for the isoviscous hydrodynamic lubrication of deep drawing and its comparison with experimental results, the effect of lubrication on die expansion that could be used as an indirect means of detecting and measuring the presence of a hydrodynamic lubricant film thickness.

ii. The improvement in deep drawing tooling that covers analysis for the blank holder, the effect of punch geometry on the deep drawing process, and introducing an alternative tooling materials for batch production.

iii. The recent developments and future direction of research.

Keywords: Deep drawing, metal forming, die expansion, lubrication, concrete tool
4.1 INTRODUCTION

Deep drawing is a sheet forming process used to manufacture a high volume product. Different shapes and sizes of products for automotive bodies, structural parts, utensils and beverage cans are manufactured by this process. The process, as shown in Fig. 4.1, involves forcing a blank or work piece into a die by using a punch. The resulting hollow component has a wall thickness nominally the same as the blank. The blank is commonly held down by a pressure plate or blankholder to prevent wrinkling of the blank during forming process. The study of formability of the sheet metal in the deep drawing has been the subject of theoretical and experimental analyses by researchers. The research areas cover analytical deep drawing [1, 2] and computational deep drawing analyses [3,4,5], development of a software package [6], new tooling materials and designs [7,8], and improving product quality and the tool’s life [9]. Furthermore in recent years due to further miniaturization of the electronic industry, demands for microforming have increased. As the aim is towards achieving reduction in size and forming thin metals [10,11] while reducing the product size to dimensions around 1 mm and using foils down to 40 μm, the classical metal forming analyses are no longer applicable and new approaches are needed for design and process control applications.

This paper aims at presenting a summary of research activities in deep drawing process at RMIT University: (i) hydrodynamic lubrication modelling of deep drawing that would

![Deep Drawing Process Diagram](image-url)
influence the tooling life and product surface quality and (ii) deep drawing tooling and new tooling materials. Future research in tailored blank drawing is also outlined.

4.2 HYDRODYNAMIC LUBRICATION IN DEEP DRAWING

Most of the available experimental work on deep drawing is concerned with the deformation mechanics of the process or the effect of lubricant on drawing force. The development of a realistic hydrodynamic lubrication model for a deep drawing process would help to improve tool life by establishing conditions to maintain a sustainable lubricant film between the tool and workpiece surfaces. In addition a better process control can be achieved.

A comprehensive study of hydrodynamic lubrication in deep drawing was studied by Shao [12]. Both theoretical and experimental analyses of hydrodynamically lubricated deep drawing were covered by Mahdavian and Shao [13]. In their study, the formation of a hydrodynamical lubrication film was considered to be in three stages: (i) the approaching stage, (ii) the yielding stage and (iii) the steady deformation stage.

Figure 4.2 shows the steady deformation stage of deep drawing stage where it is hydrodynamically lubricated.

The film thickness in the steady deformation stage was given by the following equation:

\[
h_1 = [3\mu V(\sigma _{\gamma} t_0)^{2/3} 29 p_B / \sigma _{\gamma} 0]^{1/3} [(r_0-r_1)/t_0]^{1/3} r_2
\]

![Fig.4.2](image) The steady lubricated deformation phase.
where $\mu$ is the viscosity of lubricant, $V$ is the speed of the punch, $\sigma_y$ is the material yield strength, $t_0$ is the thickness of the blank, $p_B$ is the maximum pressure limited by the blank holder, $r_0$ is the initial radius of the blank, and $r_1$, and $r_2$ are the radii of the die and die shoulder respectively.

The validity of the developed theoretical model was also investigated by a series of experiments. In these experiments the formation of a thick lubricant film was detected by applying the lubricant to dried painted blank surfaces before drawing. The establishment of a thick hydrodynamic lubricant film during the drawing process left the outside painted surface of the blank intact or partially scratched. It was also noticed that the diameter of the cup varies with the type of lubricant used in drawing process. The diameters of the lubricated cups were smaller than those of the unlubricated cups. The difference was caused by the formation of a hydrodynamic lubrication regime during the drawing process and can be used as an estimate of lubricant film thickness. The thickness of the lubricant film is estimated to be about half of this diameter difference.

The variation of film thickness with lubricant viscosity from Equation (4.1) is shown in Fig. 4.3. Comparison of experimental and theoretical results indicates that they follow identical trends. However, a direct measurement of the film thickness is required for a better comparison.

![Figure 4.3](image)

**Fig. 4.3** Comparison of film thickness

### 4.2.1 Hydrodynamic lubrication of the ironing process

The deformation of a blank of sheet metal in the presence of a lubricant film in an ironing process was considered by He [14], Mahdavian and He [15]. The measurement of hydrodynamic lubricant film thickness was related to the die expansion measurement. The analysis of ironing process was similar to Shao and Mahdavian [13] except that the viscosity dependence on pressure was considered. The minimum lubricant film thickness at the ironing zone was given by
where $R_b$ is the radius of the blank, $r$ is the radius of the partially formed cup at the edge, and $\alpha$ and $\eta_0$ are the pressure viscosity coefficient and the lubricant viscosity at atmospheric pressure respectively. The film thickness was estimated from the difference between the increased die/punch clearance, which was calculated from the expansion and lubricated cup wall thickness.

### 4.2.2 The effect of lubrication on die expansion

The influence of lubrication on the expansion of a die ring during the deep drawing of axisymmetrical steel cups was investigated by Allen and Mahdavian [16]. The work was conducted in order to determine whether the die expansion could be used as an indirect means of detecting the presence of a hydrodynamic lubricant film and measuring its thickness, or as a gauge of the product surface quality in the process. Any indications of the presence of a lubricant film in this manner would allow assessment of current theoretical models and provide a measurement for use in the control of a widely used deep drawing process. The surface finish and wall thickness of the cups produced during the experimental work were measured and evaluated to determine any correlation with the measured die expansion. In conjunction with the experimental work, finite element analysis (FEA) simulations were developed for the tooling, using values for the coefficient of friction based on the lubrication regime of the process.

Strain gauges were cemented on the outer wall of the die to record the die hoop strain. The location of strain gages and details of a single strain gage position is shown in Fig.4.4.

**Fig. 4.4** Strain gauges position on the outer wall of the die.
Axisymmetrical steel cups were produced in a hydraulic press using a circular tool steel punch and die ring. The punch has an outer diameter of 61.5 mm and a nose radius of 5.0 mm. The die ring has an outer diameter of 119.9 mm, an inner diameter of 63.7 mm and is 15.4 mm in height. The die entrance radius is 7.5 mm. A flat annular plate of steel was used as a blankholder, with the blankholder force being provided by pneumatic cylinders. Strain gauges were positioned on the outer wall of the die to record the die hoop strain. The punch force and displacement, blankholder force, and die hoop strain were recorded via digital data acquisition equipment and stored in a computer file for subsequent analysis. A general view of the press, tooling and data acquisition equipment is shown in Fig. 4.5.

Steel cups were formed from cold rolled steel sheet (BHP CA3SN-G). The circular blanks used to form the cups had an outside diameter of 120 mm and a nominal thickness of 1 mm. Prior to each experimental test the tooling was polished and cleaned with alcohol. The lubricant if required was applied to one side of the blank only, to provide lubrication between the blank and the die. The blanks were positioned in the die randomly with respect to the sheet rolling direction. This was done to randomize any influence of planar anisotropy on the resulting die hoop strain measurements. In all experiments, the blankholder load was held constant, and only the lubricant type changed.

Several lubricants were used during the experimental tests in order to provide a range of viscosities. The lubricants used were three paraffinic mineral oils of varying viscosities, and castor oil (Castrol M). The oils are listed in Table 4.1 showing their viscosities at 313 K and the designation by which they are referenced in the results. Experiments were also conducted without lubricant and these results are referenced by the lubricant type ‘None’.
Table 4.1  Lubricant designation and viscosity at 313 K

<table>
<thead>
<tr>
<th>Oil Type</th>
<th>Designation</th>
<th>Viscosity cP at 313 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Castor Oil</td>
<td>Castor</td>
<td>225</td>
</tr>
<tr>
<td>Mineral Oil A</td>
<td>Oil A</td>
<td>460</td>
</tr>
<tr>
<td>Mineral Oil B</td>
<td>Oil B</td>
<td>1070</td>
</tr>
<tr>
<td>Mineral Oil C</td>
<td>Oil C</td>
<td>1487.5</td>
</tr>
</tbody>
</table>

The average die hoop strain versus punch displacement recorded by strain gauges for each lubricant type is shown in Fig. 4.6. A punch displacement of 0 mm represents the point at which the punch makes contact with the blank. The corresponding cup height measured from the base of the cup can be determined by adding the 1 mm blank thickness to the punch displacement.

![Fig. 4.6 Average die hoop strain versus punch displacement by lubricant](image-url)

The initial negative response has been shown in subsequent experiments to be caused by the die ring rotating inwards during the deep drawing process. The major cause for this was deflection in the section of the tooling supporting the die ring. The gauge that produced the output shown in Fig. 4.6 is positioned slightly above the mid-height point of the die wall and the effect of the rotation is to cause a negative hoop strain, which is recorded by the gauge.

To eliminate the effect of the tooling deflection, the maximum tooling deflection occurring during cup forming was measured. A load was then applied to the tooling in steps until the maximum deflection was reached, with the corresponding punch force and die hoop strain being recorded. These measurements were used to determine a correction to the die hoop strain that could be applied to remove the effects of the tooling deformation. The corrected results are shown in Fig. 4.7. The small initial negative response in the corrected results is believed to be due to an inwards rotation of the die, caused by the frictional shear forces.
Advances in Manufacturing Technology

on the surface of the die ring and the vertical component of the forming force acting on the
die entrance radius. As the magnitude of the strain gauge response is clearly related to the
ratio of outer to inner die diameters it is obvious that both the shape and magnitude of the
response will be functions of the die geometry as well as lubrication conditions.

Simulations using FEA were conducted to allow comparison with the experimental results.
The simulations were performed using a commercial finite element package ABAQUS. In
order to simulate the experimental tooling, the die was modelled as an elastic solid using
axisymmetrical solid element. The blank was modelled as an elastic–plastic solid using
stress versus strain data supplied by the steel manufacturer. The punch, blankholder and
die ring support were modelled as rigid surfaces. Friction was simulated using a simple
coulomb friction model.

Typical values for external die hoop strain using various values for the coefficient of
friction between the blank and the die are shown in Fig. 4.8. The values shown are those
determined by the simulation at the same position as the strain gauge was installed on the
die ring. They show a higher strain value for lower values of friction, which is consistent
with the experimental results. Initial negative values for hoop strain due to inwards rotation
of the die are evident at the higher friction level.

In order to determine whether the die expansion as measured by the die hoop strain can
be used to detect and measure the hydrodynamic lubricant film, the factors influencing the
measured die expansion must be considered. As previously mentioned the die geometry is
one factor, however since it remains constant its influence will be neglected. Other factors
that may influence the measured die expansion are:

i. any change in the punch diameter,
ii. inwards rotation of die ring during forming,
iii. the blank and cup wall thickness and
iv. the lubricant film thickness.

During the deep drawing of cups, the blank thickness gradually increases as the blank outer diameter is reduced to the die inner diameter. This results in the cup wall thickness increasing from a point near the bottom radius to the thickest point at the top of the cup. If the gap between the punch and the die is not sufficient to allow the blank material to pass through, some reduction in the wall thickness of the cup or ironing will occur. No appreciable load normal to the surface of the punch is experienced unless ironing occurs. Ironing did occur on some cups beyond a punch displacement of 35 mm during the experiments. If we consider only that portion of the process up to and including a punch displacement of 35 mm, this effect can be ignored. Then, any change in punch diameter will only be caused by the axial load on the punch during forming, and the effect of this over the length of the punch is insignificant. The influence of any change in the punch diameter can be neglected.

Frictional shear forces on the die surface and the vertical component of the forming force acting on the die entrance radius will tend to cause an inward rotation of the die. The resultant hoop strain on the outer wall of the die is detected by the strain gauges and the magnitude and sign of this hoop strain depend on the exact position of the gauge on the outer die wall. The gauge used to produce the results reported here is slightly above the mid-height point of the die wall and hence the inward rotation led to a negative hoop strain. The negative hoop strain increases with increasing friction and forming load, and its value is superimposed on any positive hoop strain caused by die expansion. The effect

Fig. 4.8  Simulated die hoop strain versus punch displacement by friction coefficient
of this rotation is noticeable during the initial stages of cup forming producing a small negative hoop strain. The die rotation reduces the measured hoop strain by a small value proportional to the friction force and forming load, hence the effect would be greatest on the results recorded without lubricant (‘None’) and least on oil C.

The experimental results reported here have also been influenced by deflection in the support for the die ring. This deflection results in an exaggerated inward rotation of the die ring causing higher negative hoop strains than would have otherwise been recorded. As outlined earlier the results have been corrected for this deflection and the majority of its influence removed. Any remaining effects of the tooling deflection on the corrected results are believed to be minimal; however, it is possible that some residual effects exist.

The blank thickness has a direct relationship with the force placed on the die during bending and unbending of the blank over the die entrance radius. As the blank thickness increases with increasing punch displacement, the force required to initially bend the blank at the start of the die entrance radius and subsequently unbend the cup wall as it exits this radius, will increase. The radial components of these forces cause die expansion which is directly related to the blank and cup wall thickness. The change in blank and cup wall thickness may be expected then to lead to an increase in die expansion as the punch displacement increases. As discussed earlier the cup wall thickness is also influenced by the level of friction, with higher levels of friction resulting in the blank thickness reducing as it passes over the die entrance radius. This results in a reduction in die expansion due to the unbending of the cup wall as it exits the die entrance radius. The contribution to die expansion from blank and cup wall thickness should then be proportional to the level of friction resulting in higher levels of die expansion for cups formed with lower levels of friction.

The lubricant film thickness between the blank and the die also have a direct influence on die expansion. If the cup wall thickness is independent of the lubricating oil film thickness, then the die expansion increases in direct proportion to the thickness of the oil film. This assumes that the cup wall thickness varies as a result of the frictional conditions caused by the presence of the oil film and is not influenced by the thickness of the film itself. If the cup wall thickness is a function of both the frictional conditions and the oil film thickness then the resulting die expansion will be dependent on the combined thickness of the lubricating oil film and the cup wall. As the blank is drawn into the die, the volume of lubricant entering the die entrance radius will gradually increase as the lubricant coating the larger surface area of the outer blank is drawn into the die. This may lead to a corresponding increase in lubricating film thickness and an increase in die expansion as the punch displacement increases.

The corrected results shown in Fig. 4.7 can now be reviewed in combination with the above factors. The overall shape of the die hoop strain versus punch displacement curves shows an initial negative value followed by a steadily increasing hoop strain. As discussed,
the initial negative response is due to die rotation and shows slightly higher values for the lubricant types with the highest friction levels, ‘None’ and Castor. The die hoop strains increase steadily consistent with the anticipated effects of an increasing cup wall thickness and lubricant volume. A clear difference in the recorded hoop strains for cups drawn with and without lubricant exists. This difference may be due to a number of factors: the additional die rotation caused by the higher frictional shear forces and forming loads present when the cups were drawn without lubricant, the lower wall thickness or the absence of a lubricant film. The results confirm that the measured die expansion can be used to detect differences in the lubrication regime present during deep drawing; however, the exact reasons for this remain unclear.

Closer examination of the corrected hoop strains for those cups formed with lubricant indicate that the variations between lubricant types are not caused solely by the differences in cup wall thickness. The average hoop strain recorded for cups produced with oil B is higher than that for cups produced with the other lubricants, yet the average wall thickness of cups produced with oil B is less than that obtained for both oil A and oil C. The lowest level of die rotation would exist for cups produced with oil C, which also produces the highest average wall thickness and ignoring any impact of oil film thickness, cups produced with oil C would be expected to produce the highest average die hoop strains. An examination of Fig. 4.7 reveals that this is not the case, suggesting that it is possible that the oil film thickness influences the die expansion and hence the resulting die hoop strains.

The results from the FEA simulations indicate a decrease in die hoop strain with increasing friction levels. This appears to be a direct result of the cup wall thickness decreasing as the friction coefficient is increased. The simulated hoop strains rise initially as the blank enters the die, then remain relatively constant until a final rapid rise in hoop strain takes place as cup ironing commences in the simulation. The simulated hoop strains do not rise continuously in a manner consistent with the experimental results.

### 4.3 IMPROVEMENT IN DEEP DRAWING TOOLING

Deep drawing is a highly productive process capable of forming complex shapes at high production rates. However, the productivity comes at the expense of lengthy and costly tooling development. Any improvement in tools geometry will be reflected on the cost, the tool’s life, reduction of scrap, and better quality of drawn products. In the following sections the work conducted on tooling is discussed briefly.

#### 4.3.1 Blank holder analysis

A primary element of deep drawing tooling is the blank holder, which provides the in-plane tensile bias necessary to avoid buckling failure of the sheet caused by in-plane compressive strains. Blank-holder design is complicated not only by the difficult contours involved, but
also by the critical nature of sheet stability under such biaxial strain conditions. As a result, deep drawing production is often disrupted by tensile or compressive instabilities (tearing and wrinkling failure) caused by incorrect blank-holder forces. Zeng [17] and Mahdavian [18] studied the mechanism of prevention of wrinkling theoretically in order to predict the critical conditions of wrinkling in both ambient and elevated temperatures.

The formation of wrinkles in the drawing of a cup-shaped product, as shown in Fig.4.9 was studied both at ambient and elevated temperatures for the cases of free drawing and using blank holder. Experiments were conducted for aluminum blanks that were cut from 1100-0 sheet. The blanks were cut in circular shape of different diameters but within an identical thickness 1 mm. The experimental temperatures employed were 293 K ambient temperature and elevated temperatures of 373, 473 and 523 K.

For the drawing with a blank holder the critical condition for wrinkling to occur and the number of waves are estimated by the following equations

\[
\frac{\sigma_c}{E_0} = \left[ \frac{\pi a_H k (B_0^2 - \beta^2)}{6 \beta^2 \delta} + \frac{2a_B a_D (\pi^2 + 4)}{9 \beta^2 \delta^4} \right]
\]

\[
N = \left[ \frac{3 \pi^2 a_H \delta^2 k (B_0^2 - \beta^2)}{8 a_2} + \frac{4a_D (\pi^2 + 4)}{3a_B} \right]
\]

where the key parameters are given in [17] and [18].

The variations in the number of waves, N, calculated theoretically from above equation with respect to the drawing ratio at 293 K and 523 K are shown in Fig. 4.10 with experimental results.

![Wrinkling in cup drawing](image)
4.3.2 Effect of punch geometry

The effect of different punch head geometries on height, wall thickness, and surface finish of the drawn product was investigated by Mahadavian, Tui Mei Yen [19]. Four such different geometries, as shown in Fig. 4.11 have been designed and manufactured. A die with bore...
diameter 63.17 mm has been used to deform the blank into a cup shape by a punch. This has maintained the same clearance between the die and different punches throughout all experiments.

Samples used in the experiment were circular blanks cut from Aluminium 50005 H34 sheet with 1mm nominal thickness. Experiments were conducted with two lubricants engine oils Grade 130 with viscosity 19.89, Grade 6216 with viscosity 51.37 and dry condition without any lubricants. All samples were painted and dried before experiment. The painted surface allows better detection of changes on the surface condition of a drawn cup. A well lubricated product with an established thick lubricant film prevents direct contact between the surfaces of blank and tools. This results in minimal or no scratches over the painted

![Diagram of punch geometries](image)

**Fig. 4.12** Variation of the cup’s bottom thickness with punch geometry for different lubricants viscosities
surface of the blank during the deformation process. In contrast, for the unlubricated case the surface of product is scratched and even the paint is removed.

The bottom thicknesses of several cups were measured at different locations and the average values for different punch geometries and lubricant viscosities are plotted in Fig. 4.12.

The deformation of the wall and the bottom of the cups can not be evaluated independently due to the deformation continuity. To demonstrate a better picture of the cup’s deformation, the ratio of measured wall thickness to the bottom thickness has been plotted in Fig. 4.13. It reveals that for non-lubricated condition reducing the contact surface between the blank and punch’s bottom leads to reduction of friction force. Consequently, the deformation is more homogenous and thickening of blank becomes more significant and dominates the stretching process. This a further indication of existence of high friction coefficient for all punch profiles.

![Graph showing the variation ratio of wall to bottom thickness of drawn cups with punch geometry.](image)

\textbf{Fig. 4.13} Variation ratio or wall to bottom thickness of drawn cups with punch geometry.

For all punches, the presence of lubricant in the drawing process extends the stretching to the bottom part of a cup and this effect is well revealed for flat and bored punches. The profile of the punch is important in establishment of a thick lubricant film and this has been reflected on the degree of surface roughness of the cup. The radial punch geometry produces a film thickness that is more than the other punches in general. Further work is needed to study other punch geometries with emphasis on punch radius and their effects on friction force and stretching of the bottom part of a cup.

\subsection*{4.3.3 Development of concrete tool}

In most manufacturing processes tooling costs are significantly high. Most tools used for metal forming processes are made from alloy steel and can withstand impact or severe loading at either room or elevated temperatures. The high cost of tooling for these processes
can be economically acceptable and justified if they are used for high volume or mass production. If there are needs for limited or batch production, and flexibility in product shape that requires changes in tooling then these processes become costly. Hence, advantages such as fast production, good surface finish of products and equipment simplicity are lost if alternative processes are considered for replacement. The current technologies in metal forming processes are incapable of responding quickly to the continuous changes of tools for new products. Development of new materials as a replacement for alloy steels is essential to improve functionality in a high responsive manufacturing environment where the deep drawing process is used.

Allen and Mahdavian [20] reviewed the development of a concrete tool for sheet metal forming by deep drawing. A stress analysis as shown in Fig. 4.14 for a simple deep drawing die was conducted to estimate the stress levels in the die. Various types of concrete in two types of mould, a square concrete die and a circular concrete die with stepped steel ring were cast. The circular concrete die with stepped steel ring is considered a better design and uses less concrete (Fig. 4.15). Commercial CemliteHe composite material has properties and characteristics better suited for use as tooling than the other concrete mixtures tested to date. However improvements in the properties of dies produced with this material are still required. It is believed that this can be achieved through the use of suitable additives. Further research is required to allow further application of concrete to tool materials. The low cost of the base material, combined with the use of rapid prototype techniques for the production of moulds will make concrete a suitable material for tooling in sheet metal forming processes in a responsive manufacturing environment.

![FEM stress analysis for the die.](image-url)
4.4 deep drawing of tailored blanks

In auto industry, the reduction of components’ weight and improvement of products strength have been considered seriously in recent years. This has led to the development of new materials or manufacturing processes. The use of a single blank with multiple thicknesses, the so called tailored blank, cut from sheet metals with different thicknesses and welded together by laser welding and then drawn into a product shape has become popular. Manufactured products can have less weight and in some locations may even have been strengthened by increased thickness. Drawing tailored blank in a deep drawing process requires different tooling design and process control from traditional deep drawing of a blank with uniform thickness. The introduction of tailored blanks in deep drawing process has brought new areas of research and development in this field.

Research in deep drawing of tailored blanks is in progress in advanced manufacturing processes at RMIT University. The results will be available in near future.

4.5 conclusions

The review of theoretical and experimental work in deep drawing shows that each components of deep drawing tooling requires attention in order to secure product quality, reduction in scrap and tool life and performance. Further work in refinements of theoretical work and experimental measurements will assist a better control and a more realistic simulation of the process. Revisiting both previous experimental and theoretical work on deep drawing
of tailored blank and microforming of deep drawing will lead us to identify future research needed for these processes.

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References


