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A Review of Methods aimed at Improving the Draw Ratio in the Deep Drawing Process

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*A new deep drawing process for the manufacture of very deep cups from sheet metal is being investigated and developed by the authors. A drawing rig (**Figure 1**) which uses the friction activated blank holding, an adjustable die and hydraulic pressure has been designed and manufactured. Possible advantages regarding limiting drawing ratio and thickness strain distributions were investigated. Other methods of improving the draw ratio were also studied. For example, new methods of hydraulic counter pressure drawing and hydraulic augmented drawing have been developed by **Nakamura et al** and **Thiruvarudchelvan et al**, in which hydraulic pressure is used to apply a force in the radial direction to assist in the drawing of sheet metal. These processes along with others are reviewed in detail.*

1. Introduction

In the field of sheet metal forming, the most important feature is that any desired product should be formed successfully without fracturing or wrinkling and many new sheet materials with good formability have been developed to this end. At the same time, the requirement for accuracy in formed products has been increasing because automatic assembly has come to be applied to sheet formed parts also. It is difficult, however, to obtain sheet formed products of high accuracy and consideration must be given to the various causes of inaccuracy.

Sheet metal forming includes the sheet metal forming operations such as shearing, bending, drawing, spinning, roll forming, stretch forming and bulging to form a variety of products. The distinguishing characteristics of sheet metal products are that they have a large surface area and a low modulus (ratio of volume to surface area) as compared to products produced by casting, bulk deformation or machining. In general, sheet metal forming is a two-dimensional deformation because the thickness change is generally small, but the elastic recovery can be significant. Since the operations are often performed on presses, sheet metal forming is sometimes referred to as press-working.

Due to the high ratio of surface area to volume for a thin sheet metal blank, the interaction of the surfaces of the sheet metal and the tooling with each other and with an applied lubricant determines, to a large extent, the success of any sheet metal forming process. This is especially true for processes such as deep drawing, which involve moderate to severe working of the metal.

In the simplest form of deep drawing, a circular blank of sheet metal is supported between a die and a blank holder and is formed into a cup by a cylindrical punch.

In deep drawing operations, forming is carried out with tools (rigid and flexible), active media (e.g., sand, steel pellets, liquid) or active energy (i.e., a magnetic field). The role of the blank holder is to provide sufficient pressure on the flange to prevent it from wrinkling. If the blank holder pressure is too high, or the drawing ratio is too high (blank original diameter/punch diameter), the punch, instead of drawing the metal around the die profile radius into the die cavity, fractures the wall of the cup and punches through.

The main purpose of this research project then is to form deep components without fractures or wrinkles in the flange. The depth of a drawn product

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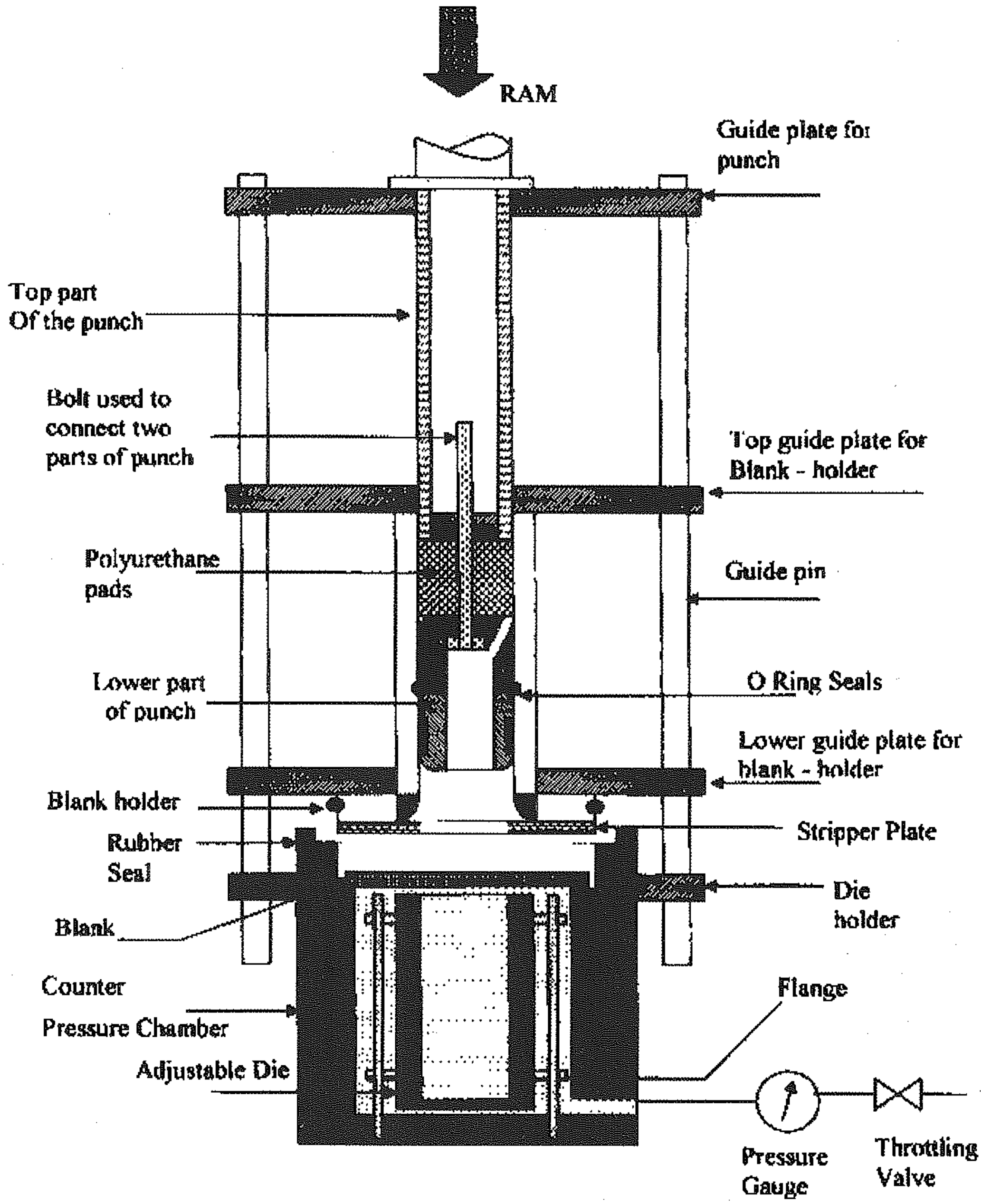

FIGURE I: *A Sectioned Front View of the Deep Drawing Rig* thus depends on a number of parameters that constantly change durng the forming process and the above example serves to illustrate how a component can fracture if the blank holding force is too great.

Other conditions that affect the depth of draw are deformation of material, tool geometry, forming speed, surface roughness, type of materials used for drawing, blank diameter, contact pressures and lubrication conditions.

The following paragraphs give some insight into recent research being carried out by scientists to improve the deep drawing process and the draw ratio as well as a review on the use of flexible tooling in the deep drawing process.

2. Sheet Metal Forming Using Flexible Tooling

In this type of forming, a flexible polyurethane pad is used as the female die, instead of the conventional metal die. This has many advantages associated with it such as preservation of work piece surface among other things and will be discussed in detail later on in this section.

Flexible tools such as polyurethane have been used in metal forming from the latter part of the 19th century. In the early days, natural rubber was used but with the number of synthetic elastomers, such as urethane, with superior properties available today the scope for the use of flexible tools has increased. Urethane pads, rods and tubes are commonly used in dies as pressure pads, stiff springs and cushions.

Rubber pad forming, also known as flexible die forming, employs a rubber pad as one tool half, requiring only one solid tool half to form a part into its final shape. The solid tool half is usually similar to the punch in a conventional die, but it can be the die cavity. The rubber acts somewhat like a hydraulic fluid in exerting nearly equal pressure on all work piece surfaces as it is pressed around the form block.

Rubber pad forming is designed to be used on moderately shallow parts having simple flanges and simple patterns. The production rates are relatively high, with cycle times averaging one minute or less.

The advantages of using the rubber pad forming process compared to conventional forming processes are:

1) The elimination of the need for a matched set of male and female dies. Only a male or female die is needed with the elastomer forming the other part.

2) The work piece surface is not marred. The surface of the work piece in contact with the elastomer can be pre-polished, pre-printed or pre-plated eliminating the need for a protective coating.

3) The process can accommodate several thicknesses of the sheet metal being formed.

4) Alignment and mismatch problems are eliminated.

5) Spring back after forming is minimal.

6) Tools are low in cost (range from 30% to 80% of those for hard steel dies).

7) Thinning of the work metal, as occurs in conventional deep drawing is reduced considerably.

8) The forming radius decreases progressively during the forming stroke, unlike the fixed radius on conventional dies.

Disadvantages of the process are:

- Rubber wears out quickly or tears on sharp projections.
- Shrink flanges may have wrinkles that need working out.
- Lack of sufficient forming pressure results in parts with less definition and sharpness.

- The main equipment used in most rubber pad forming processes is a hydraulic press which is costly.

Metal forming processes where flexible tools are used include sheet metal bending, cup drawing, embossing and piercing.

The most significant factor controlling the application of metal working as a manufacturing process is the ductility of the work piece. The fact that ductility or lack of it is not an inherent and solely metallurgical property, but a property that can be controlled by mechanical means, namely environmental pressure.

Numerous tensile experiments were carried out on several metals with various levels of superimposed environmental pressures. It was observed, as general trends, that ductility and strength increased as hydrostatic pressure increased. Further observation showed that many materials formed under pressure retained some residual improvement in ductility. When a tensile test in a pressurised chamber was interrupted before fracture and the specimen was removed and reloaded in tension under atmospheric pressure, the subsequent ductility was higher than when the specimen was loaded in an atmospheric environment for the entire test.

It was proposed then, that pores opened in the necked region and these later lead to failure. The superimposition of high environmental pressure suppressed the opening of the pores, thereby extending ductility. **Alexander *et al*** [1960] subsequently confirmed these initial observations and proposed a mechanism of failure.

With this in mind, some of the recent forming processes that have enhanced the deep drawing process over the years will be presented and discussed.

3. Improvements to the Deep Drawing Process

3.1 Friction Actuated Blank Holding

During the last few years, a technique of friction actuated blank holding using polyurethane pads has been developed by **Thiruvarudchelvan** and **Lewis** [1987, 1988, 1990] for the drawing of cylindrical cups. Here, the friction between the rubber pad and the blank holder generates the blank holding force automatically. In this process, an annular urethane pad incorporated between two parts of a steel punch expands radially outwards when the drawing force is applied to the punch. As the urethane pad is confined in the bore of the blank holder, blank holding force is generated automatically by friction when the punch moves to draw the cup.

Theoretical models have been developed to predict the approximate drawing force and blank holding force. The blank holding force measured when drawing with this process was found to be approximately proportional to the drawing force. The advantages of using this type of blank holding are as follows:

(1) When the punch load is small, the blank holding force will also be low, thus minimising the static frictional resistance against drawing at the start. This will help to minimise the possible fracturing of the cup at the start especially with the larger draw ratios.

(2) When the drawing load is maximum, (i.e., when the tendency to wrinkle is also maximum), the maximum blank holding force will be applied to suppress wrinkling.

This technique therefore elimiuated the constant force blank holding and prevented excessive thinning of the metal between the blank holding surface and the die surface which may cause the metal to break off and become trapped between these surfaces.

The results from these tests indicated lower punch force and modest increases in the limiting draw ratio and less thickness variations when compared with cups formed under constant force blank holding.

3.2 Drawing of Cylindrical and Hemispherical Cups Using An Improved Tooling for Friction Actuated Blank Holding

Since the conception of the principle of friction actuated blank holding for deep drawing in 1984, considerable effort was devoted to the investigation of various aspects of the concept and its applications.

Since then, **Thiruvarudchelvan** and **Loh [1993]** have developed an improved tooling for the drawing of cylindrical and hemispherical cups.

In this new tooling, a rubber shroud was put in place to prevent wet lubricants from reaching the friction interface. This shroud thus retains any lubricant that may have come into it through the punch - blank holder interface, effectively sealing the urethane pad - blank holder interface from the lubricant. With this improved tooling, moderate increases in the limiting draw ratio were realised.

3.3 Application of Ultrasonic Vibration to the Drawing Process

In 1998, **Jimma *et al* [1998]** and others developed experimental apparatus whereby the blank holder or die plate could be vibrated in a radial mode. Upon application of 20 kHz and 28 kHz oscillations, the limiting drawing ratio increased from 2.68 - 3.01 for cold rolled steel for deep drawing, 2.38 - 2.77 for stainless steel and 2.58 - 2.94 for cold rolled steel.

It was also noted that greater accuracy and deeper cups could be formed by stopping the oscillation after the maximum punch load is reached rather than applying the oscillation throughout the deep drawing process.

It was also stated that for the rise in the LDR, the blank holder and the die plate should be simultaneously vibrated in anti-phase to each other.

3.4 Deep Drawing Through Tractrix Type Dies

Campion [1976] who examined the Kellver System and the advantages resulting from a die of the tractrix form carried out other investigations into improvements in the deep drawing process. The tractrix die is used to increase the limiting blank size because of its increasing radius of curvature along the die profile. Furthermore, the use of a tractrix die eliminates the need for a blank holder, thereby greatly simplifying the drawing tools.

Al-Makky and **Woo [1980]** investigated the advantages of using the tractrix die in the deep drawing process and found that the punch load was greatly reduced due to the large radius of curvature. They also noted that for some materials, a gradual increase of radius of curvature in the die lip region is necessary so as to prevent these materials from buckling in the early stages of drawing.

3.5 Deep Drawing without Lubricant by Use of Diamond-like Carbon-coated Dies

Deep drawing of sheet metal for such parts as automotive components presents problems; one being the ease with which the sheet metal adheres to the tools, such as deep drawing dies, resulting in the necessity for heavy lubricants.

Since these lubricants require strong degreasing agents, like 1,1,1-trichloroethane, which is detrimental to the environment, studies have been pursued by **Murakawa, Koga** and **Kumagai [1995]**, to find alternative lubricants with much lower viscosity that can eliminate the need for harmful degreasing agents.

The authors proposed the use of a diamond-like carbon (DLC) film coated onto the die in order to deep draw aluminium sheets without lubricant.

The use of the DLC coating was found to eliminate the need for any lubricant to prevent adhesion of aluminium to the die material during up to about 6200 deep drawing operations in which square cups were produced.

In contrast to the DLC coated die, an uncoated WC-Co alloy deep drawing die opoerated without any lubricant caused fracture of the aluminium sheet after only five repetitions of deep drawing because of the strong adhesion of the material to the die. This shows the dramatic effects of the DLC coating.

3.6 Developments in Multi-point Die Cushion Technology

Improvement of the deep drawing process regarding efficiency and product quality is established by the reduction of scrap, faster start-up after a tool change and improved means for reaction to parameter fluctuations such as material or lubricant properties. One key factor is the control of material flow by the corresponding control of the blank holder pressure. Conventional single or double action press systems do not offer the means of adjusting a pressure profile that suits specific part geometry in an optimal way. This causes increased tool run times, extended tool change times and high scrap rates for critical forming tasks.

Pahl [1997] describes a new generation of the multi-point control system consisting of a hydraulic press, a multiple cylinder unit for the blank holding function and flexible forming elements as punch drive.

Based on the principles of separating the blank holder function from the slide operation, part geometry related blank holder cylinder pattern and providing of centric loading of the forming elements, improved process stability is achieved. The introduction of a PC-based control system using MS-Windows for the operator interface and a PLC as software emulation ensures an easy handling of the complex parameter adjustments.

The results of this are reduced set-up times, minimised material consumption as well as a reduction in the scarp rate. When applied to the field of forming of stainless steel kitchen sinks using costly material, the improvements in process control can be verified.

3.7 Laser-assisted Deep Drawing (LADD)

In principle, manufacturing processes can be divided into three categories. These are processes with material removal (e.g., drilling, cutting or machining), processes with material addition (e.g., cladding or welding) and processes where neither material is added nor removed, for instance deep drawing. The first two processes have been conquered to a large extent by lasers, since they involve geometries with a narrow processing zone that extends along the processed parts, as for instance the cut contour or weld seam which suits the small focal size of a laser beam perfectly.

Laser technology was not well-suited to deep drawing because the process is essentially two-dimensional and requires the use of mechanical forces and cannot be realised with laser beams to date.

Schuöcker, Schröder and **Zeinar [1999, 2001]** conceived the idea of laser-assisted, deep drawing and successfully realised it at the University of Technology, Vienna. They proposed that the selective heating of sheet metal during the deep drawing process by using laser irradiation gives the possibility both of reducing the drawing force and of increasing the maximum drawing ratio.

Both effects are highly desirable since they help to make deep drawing more efficient. The elevated temperature weakens the bonds between the metal atoms and facilitates deformation, for instance by easing dislocation movement. It was shown experimentally and theoretically that a properly chosen local heating of the work piece results in a global change of the drawing process.

It was demonstrated that a reduction of the drawing force of up to 30% and an increase of the drawing ratio of 10% (1.67 - 1.77) could be achieved by this LADD.

3.8 Hydraulic Concrete as A Deep Drawing Tool

The body of the car contains more than 300 deep drawn parts. Their sizes range from a few centimeters to more than a metre. In the automobile industry, the deep drawing tools are usually made of polymer resin concrete (PRC) covered by a gel coat which is a metal-charged resin. When the parts need a severe deep drawing involving important stresses in the tools, the tools are machined in a metal-charged epoxy resin. Thus, the production costs of a prototype car are very high.

Hence, the sheet metal manufacturers have to offer new technical innovations to reduce the costs of forming sheet steel to the manufacturers. It was then realised that the reduction could occur at the stage of manufacturing the deep drawing tools used to produce the prototype cars.

Schwartzentruber, Bournazel and **Gacel [1999]** proposed to reduce the production costs of prototype tools by using high performance hydraulic concrete (HPC) in place of the PRC. Due to the mechanical properties of the HPC, it was able to replace the PRC.

Nevertheless, during the deep drawing operations, the friction of sheet steel on the surface of the tools induced important stresses. To limit the abrasion, a gel coat was applied to the HPC.

By using the HPC tools, more than 16,000 parts could be drawn as compared to 50 parts with the PRC tools. Consequently, HPC which is eight times less expensive than PRC, was able to markedly reduce the manufacturing costs of prototype tools.

3.9 Hydraulic Counter Pressure With Radial Pressure

This method was put forward by researchers - **Nakagawa, Nakamura** and **Amino [1984, 1985, 1986, 1987, 1997]** and was used as a means to overcome the restrictions of deep drawing. The use of its merit includes forming of tapering shapes and complicated shaped, achieve higher-forming limits and higher accuracy of formed parts. Economical advantages such as reduction of sheet metal material costs and die costs are also included. This method is also being applied to the forming of automobile body parts due to its die manufacturing cost-reduction merit. The process is carried out as follows:-

A punch is pressed on a blank piece into a counter pressure chamber. This chamber is filled with liquid whereby hydraulic counter pressure is generated by the pressing. The pressed blank piece is forcibly followed in shape around the punch by hydraulic counter pressure, while part of the hydraulic counter pressure is automatically supplied to an outer circumference of the blank piece via a bypass passage.

The hydraulic pressure serves as a compression force from the outer circumference of the flange to the radius direction. The pressure serves as a pressing force towards the axial direction of a sidewall of the product. The liquid also serves as lubrication on the upper and lower surfaces of the blank piece.

3.10 *Hydraulic Pressure Augmented Process*

This process was put forward by **Thiruvardchelvan *et al* (1995, 1998)**. In this method, high hydraulic pressure proportional to the punch force generated in the tooling augments the drawing action of the punch and provides blank holding and lubricates the blank-tool interface.

In this process, pressure is also applied to the rim of the blank to give a pushing effect. There is also automatic coordiuation of the punch force, hydraulic pressure and blank holding force.

There is low friction between the blank and tooling as high pressure lubricates these interfaces. With this process, only a single action press is needed unaided by a cushion. Draw ratios of 3.5 have been reported with this method.

4. Deep Drawing Process Using Friction-Activated Blank Holding, Hydraulic Pressure and An Adjustable Die

This drawing rig operates on the principle whereby a punch advances onto a blank piece into a chamber filled with liquid. Hydraulic couuter pressure is generated which serves to push the periphery of the blank onto the punch (see **Figure 1**).

The object of this drawing rig is to provide a novel sheet metal-forming process utilising hydraulic pressure and friction-activated blank holding to improve the draw ratio in a simple manner on a single action press without requiring special devices or complicated set-ups.

To accomplish these objectives, the proposed rig adopted a modified process in which the characteristic of the drawing by the counter pressure method is used, while the counter pressure is utilised as a compressive force and the fluid serves as lubrication between the blank and the blank holder.

The counter pressure generated is automatically supplied around the blank piece through the clearance between the flanges attached to the adjustable die and the inner wall of the counter pressure chamber. The compressive pressure is applied to the edge of the blank while the forming is carried out with the hydraulic counter pressure providing fluid lubrication on both sides of the blank.

The punch radius allows for sufficient friction to avoid sliding and thinning at the sidewall portion of the blank in this region. On the other hand, the radial pressure at the flange reduces the tension force generated in the sidewall of the component being formed and the friction reducing effect may be produced on both faces of the blank piece.

Furthermore, the drawing rig employs the hydraulic pressure and friction-activated blank holding, which is spontaneously generated by the pressing of the punch. Thus, the rig does not need any special device for supplying the radial pressure or blank holding nor require high pressures to obtain the pushing effect at the flange.

The conventional deep drawing process continues to be widely used because of the simplicity of the tools and the high volume of production possible. While using conventional deep drawing, the method of blank holding used may not apply an optimum blank holding force at every stage of the draw. It makes use of the minimum constant blank holding force necessary to prevent wrinkling throughout the process.

In this process, friction-activated blank holding is utilised to apply the blank holding force. The maximum blank holding pressure is applied when the maximum circumferential stress occurs in the flange region of the partially drawn component. Thus, the frictional drag against radial drawing is minimised. In this way, excessive stresses, stretching and thinning may be minimised when compared with the application of a constant blank holding force to prevent wrinkling.

5. Drawing Operation of the Proposed Die Rig

When the deep drawing operation is undertaken in the present rig, a liquid is filled in the hydraulic counter pressure chamber and the blank is placed on top the opening in the chamber. Subsequently, the punch and blank holder begin to advance.

In this way, the lower face of the blank holder contacts the upper face of the projecting circumferential wall and the blank is now enclosed in a ring-like space whose upper side is closed. There is also a space between the edge of the blank and the projecting wall.

At this stage, the liquid may be filled up to the bottom of the blank or a little below as this will determine whether the hydraulic pressure will be generated from the start of the downward movement of the punch.

When the punch moves down and draws the blank into the pressure chamber, a counter pressure is spontaneously generated within the pressure chamber and the blank piece is closely contacted to the shoulder of the punch so that the bottom of the cup starts to form and a side wall is gradually formed by drawing of the punch. At a predetermined level of pressure, a throttling valve will open to release pressure in the chamber so that the punch can advance to complete the drawing operation. This set level will ensure that the fluid pressure is sufficient to help effectively press the edge of the blank onto the punch.

Since the counter pressure contributes to the forming of the sidewall, a friction-keeping effect could be obtained. Also, fluid lubrication is effected on the lower surface of the blank.

In the drawing rig, the fluid is contained within the ring-like space between the adjustable die and the hydraulic counter pressure chamber. Therefore, the high pressure generated causes the fluid to go upwardly into the ring-like space and reach the outer edge of the blank. Thereby, the hydraulic pressure directly acts on the outer circumferential edge of the blank in the radial direction. Thus, the blank is drawn to the determined stroke by the punch advancing.

Due to these conditions, the tension induced in the sidewalls of the formed component is reduced when the drawing is carried out. Furthermore, the hydraulic pressure compressing the material in the radial direction escapes to the upper side of the ring-like space that is between the lower surface of the blank holder and the upper surface of the blank.

Consequently, the fluid lubrication effect is also provided between the upper surface of the blank and the lower surface of the blank holder. Thus, both surfaces of the blank benefit from the friction-reducing effect.

In most deep drawing operations, the blank holder is stationary, therefore, while drawing, a blank holding force of a determined value is kept.

If the space was too small, the blank holding force would be too strong and the fluid lubrication would not be smoothly effected so that the friction-reducing effect would be unsatisfactory. This could cause that material to fracture prematurely. On the contrary, if the space was too large, the hydraulic pressure would not be sufficient (as with the throttling valve mentioned earlier) to push the edge of the blank and breakage or wrinkles could occur on the product.

To avoid these concerns, the method of friction-activated blank holding was introduced into the drawing rig. In this method, the blank holder applies a force that is proportional to the drawing force. With this type of blank holding, the maximum blank holding pressure is applied when the maximum circumferential stress occurs in the flange region of the blank.

Thus, the frictional drag against radial drawing is minimised. Also, excessive stresses, stretching and thinning may be minimised when compared with the application of a constant blank holding force.

Investigations also showed that the application of a blank holding force which is approximately proportional to the punch force, gave a reduction in the punch force needed to draw a cylindrical component.

6. Conclusion

In the literature review, it has been shown that various methods of improvements to the deep drawing process have been studied in some detail and the authors have put forward a novel approach to enhancing the draw ratio in the same process. The novel drawing rig possesses great potential for improvement of the draw ratio in the deep drawing process.

With a reduction in stretching and thinning at the base of the wall of the cup near the punch radius region (shoulder) and with the help of the "pushing effect" of the hydraulic pressure and lubricating effects, an increase in the draw ratio can be achieved with this new rig.

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