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Numerical simulation and analysis on the deep drawing of LPG bottles

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ABSTRACT

Deep drawing is one of the most used sheet metal forming processes in the production of automotive components, LPG bottles and household goods, among others. The formability of a blank depends on the process parameters such as blank holder force, lubrication, punch and die radii, die-punch clearance, in addition to material properties and thickness of the sheet metal. This paper presents a numerical study made on the deep drawing of LPG bottles. In particular, the application of both variable blank holder forces and contact friction conditions at specific location during deep drawing are considered. The numerical simulations were carried out with DD3IMP FE code. A variable blank holder force strategy was applied and the numerical results were compared with results from other blank holder force schemes. It is evident that the proposed variable blank holder force scheme reduces the blank thinning when compared to other schemes; the friction coefficient also has a significant influence on the stress–strain distribution.

1. Introduction

The choice of a material for a given application depends on its functional capacity and in-service requirements. Due to the high-pressure application and hazardous nature of the liquefied petroleum gas (LPG), the fabrication integrity of LPG bottles is an important specification. The reliability of the gas bottles is fundamentally bound to the quality of the material, in addition to the forming and welding procedures. As the bottles are subjected to a number of damage mechanisms such as mishandling during transportation, fatigue, corrosion, etc, any defects incurred during manufacturing will limit the service life and sometimes become unsafe. In general, the formability of the chosen blank depends on the process parameters such as blank holder force, lubrication, punch and die radii, die-punch clearance, in addition to mechanical properties, thickness and part's geometry. Of all these parameters, the blank holder force and the friction condition between the blank and the forming tools play a major role on the flow characteristics of the blank. In deep drawing, using proper blank holder force is an essential criterion to restrict wrinkling tendency and avoid tearing of the blank. Similarly, proper friction condition enhances the flow of material into the die cavity. The objective of this investigation is to optimize both the blank holder force scheme and the friction condition in order to optimize the forming process of gas bottles.

Fazzini et al. (2002) conducted an experimental study on the effects of welding defects in LPG bottles. The fabrication defects grow in service and cause failure of the gas bottle if the growth reaches a critical value during service. The presence of defects dramatically reduces the reliability of the gas

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bottle due to stress concentration and residual stresses. Neil Krishnan and Jian Cao followed a strategy to optimise the blank holder force history to maintain predetermined wrinkling amplitude under the blank holder (Krishnan and Cao, 2003). This was achieved by varying the blank holder force depending on the wrinkling tendency. With a similar objective, Sheng et al. (2004) used a feedback controlled adaptive strategy to vary blank holder force based on the punch force evolution. Both flange and side wall wrinkling tendency was considered in this study to implement the strategy. A number of similar research works published emphasis the importance of variable blank holder force in deep-drawing process. A brief review of various aspects controlling wrinkle and fracture in a sheet metal part has been presented in reference (Obermeyer and Majlessi, 1998). Thiruvarudchelvan (1995) devised a hydraulic equipment to apply blank holder force proportional to punch force to suppress wrinkling. Traversin and Kergen (1995) utilised a closed-loop blank holder pressure regulation system based on punch force and wrinkle occurrence. The system adjusts the blank holder force continuously to obtain the minimum force needed to avoid wrinkles. Gunnarsson et al. (1998) investigated degressive, constant, progressive blank holder trajectories to establish the process window and LDR. For smaller blank sizes, the process window between the wrinkle and fracture limits can be increased using the degressive blank holder force. In another study, a strong–weak variable blank holder force scheme has been used to increase the dent resistance of a shallow double curved panel and decrease the springback (Gunnarsson and Schedin, 2001). Yoshihara et al. (2005) observed that a weak–strong variable blank holder force scheme improves the limit drawing ratio of magnesium blanks.

Literature suggests that the limiting drawing ratio (LDR) is a function of in-plane anisotropy, strain-hardening exponent, friction coefficient, die radius, half die opening, and yield strength (Duchêne and Habraken, 2005; Leu, 1999; Verma and Chandra, 2006). The influence of these parameters can be estimated using finite elements simulations thus saving material and time expended on experimentation. A range of forming parameters can be used in the finite element simulations and the optimal values can be predicted at low-CPU cost (Mamalis et al., 1997). This paper presents the investigation made on the effect of varying both the blank holder force and contact friction condition on the thickness distribution in deep-drawing process. An appropriate method to maximize the minimum thickness and minimize the maximum thickness is suggested.

2. Deep-drawing simulations

2.1. DD3IMP

Numerical studies are capable of revealing the deformation pattern of the blank, characterising materials under industrial deep-drawing conditions, to result in an optimal final solution. In this study, deep-drawing simulations were carried out using the in-house finite element code DD3IMP (contraction of Deep Drawing 3d implicit code), which is specifically developed to simulate sheet metal forming processes (Menezes and Teodosiu, 2000). Due to geometrical (axi-symmetry) and material symmetries, only a quarter of the LPG bottle is considered in the simulations. The values of punch force and blank holder force presented in this paper corresponds to the deep drawing of a quarter of the bottle. Symmetry conditions are imposed on global XZ and YZ planes in the finite element mesh and the punch travels parallel to the global Z-axis. The forming tools are considered to behave rigidly. The tools are defined by parametric Bézier surfaces. For clarity in visualising, the forming tools used in the simulation are described with triangular elements in the post-processor, Fig. 1. The geometry of the forming tools is shown in Fig. 2.

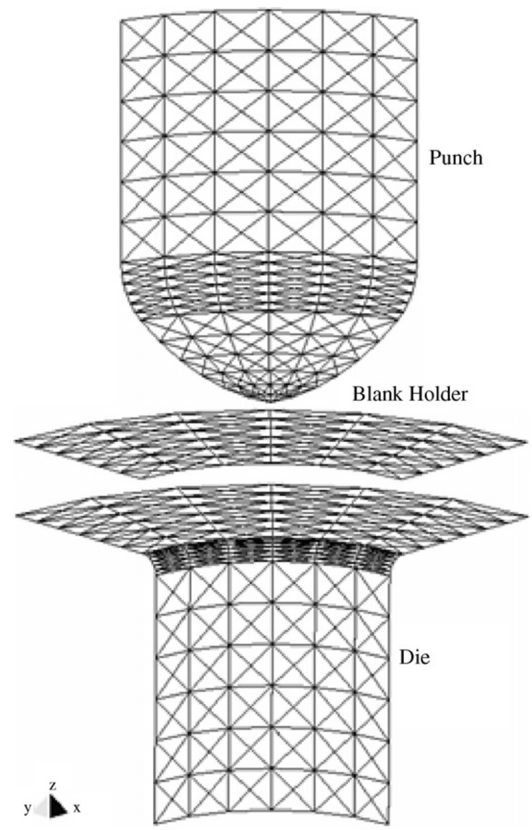

Fig. 1 – Tools used in the simulation.

2.2. Material

The material used in this study is an austenitic grade (AISI 304) stainless steel (Antunes et al., 2002). It has superior corrosion resistance due to the presence of 18–20% chromium. In addition, it has excellent heat resistance with good mechanical properties over a wide range of temperatures. The chemical composition is given in Table 1a and the mechanical properties in Table 1b.

E is the young's modulus, ν is Poisson's ratio and Y is the yield stress of the material. The work-hardening behaviour is considered isotropic and described by the Swift power law: $\sigma = K(\varepsilon_0 + \bar{\varepsilon}^{\mathrm{P}})^n$, where σ is the flow stress, K the strength coefficient, ε_0 the proof yield strain, $\bar{\varepsilon}^{\mathrm{P}}$ the equivalent plastic strain and n is the strain-hardening exponent with the plastic anisotropy described by the Hill48's quadratic yield criterion (Hill, 1948). Hill'48 yield function is widely used in finite element simu-

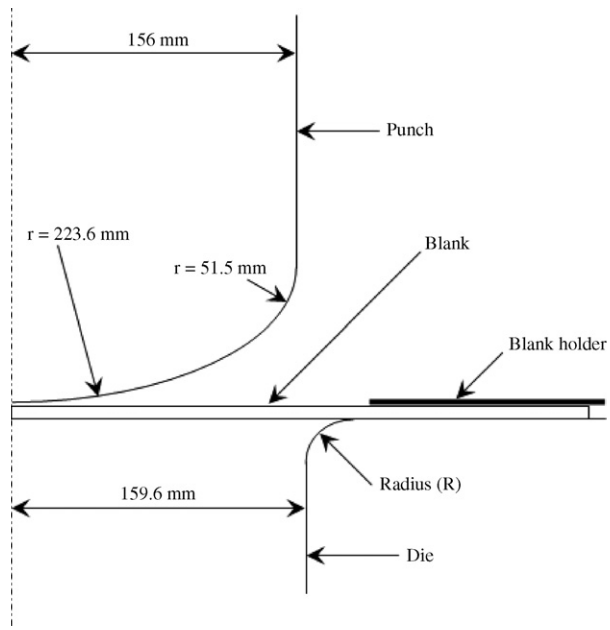

Fig. 2 – Geometry of the forming tools.

Table 1a – Chemical composition of AISI 304 stainless steel

C	0.08
Cr	18–20
Fe	66.345–74
Mn	2
Ni	8–10.5
P	0.045
S	0.03
Si	1

lation studies and has been very useful for explaining some phenomena associated with plasticity. The flow stresses can be closely predicted for materials with average *r*-value close to unity (Kuwabara et al., 2002), while the strain distribution can have deviations. The deviations can be mainly due to equi-biaxial stretch conditions (bottom of the cup) where Hill'48 model may predict thinning. However, the main objective of this study is to increase LDR of the blank and the average *r*-value for the stainless steel used is 1.105. The initial blank has a radius of 320 mm and a thickness of 3.5 mm. The blank is meshed with eight node solid finite elements. An in-plane average FE mesh size of 7 mm was used with two layers through thickness.

Table 1b – Mechanical Properties of AISI 304 stainless steel

E (GPa)	200
ν	0.33
Y (MPa)	300
ε_0	0.009
K (MPa)	1330
n	0.35

2.3. Blank holder force schemes

The range of blank holder force between tearing and wrinkling depends on the material properties, drawing ratio and the geometry of the cup to be drawn. The high value of the strength coefficient (*K*) of the chosen material limits the deep-drawing process with a constant blank holder force, because a high-value leads to excessive thinning and a low-value leads to wrinkling. The mechanical behaviour of the blank and decreasing area of the flange require the blank holder force to change accordingly. One of the design objectives of this study is to achieve a thickness not less than 2.6 mm in the formed cup. The gas bottle application necessitates trimming the flange formed in the cup after deep drawing to facilitate welding to the other half. Thickening occurs only at the flange area and hence it is not important to restrict thickening in the part. The lowest blank holder force necessary for the cup to eliminate wrinkling in the initial stages is found to be 30 kN and hence this force formed the basis for blank holder force schemes. An appreciable increase in the frictional force between the blank and the tool is inevitable when the blank passes over the die radius. As the contact condition changes, an improved surface finish at the die radius may well reduce this tendency of increasing friction force, enabling a smooth flow of the blank into the die cavity. Recent developments in hard and solid lubricant coatings indicate that portions of the forming tools can be coated to reduce friction between the tools and the blank (Vanhulsel et al., 2007; Neville et al., 2007). This will improve the flow behaviour of the blank, eliminates the need for harmful oil lubricants and results in a healthy environment. Since the material considered in this study is a stainless steel, a proper blank holder force scheme and friction condition becomes vital for the success of this deep-drawing operation.

Different blank holder force application schemes have been investigated in this study, which are presented in Fig. 3. A low-blank holder force of 30 kN was applied all through the punch displacement (LF) to elucidate wrinkling threshold and development. At the end of deep-drawing process, large blank holder force is necessary to contain blank holder force displacement due to small flange area. Thus, a high-blank holder force scheme (HF) was studied. However, a high-blank holder force restricts the flow characteristics of the blank and hence

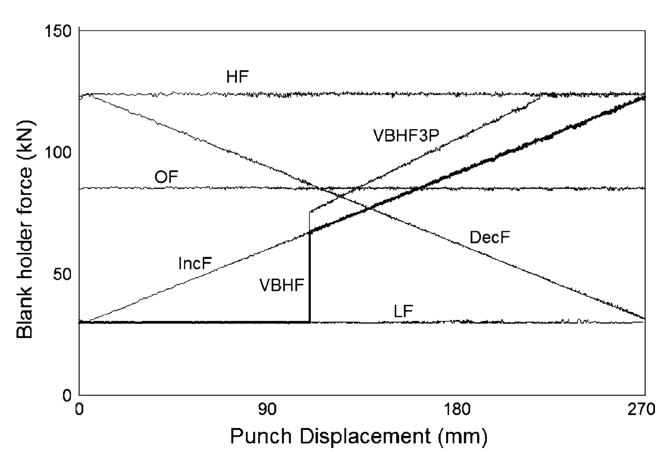

Fig. 3 – Blank holder force schemes.

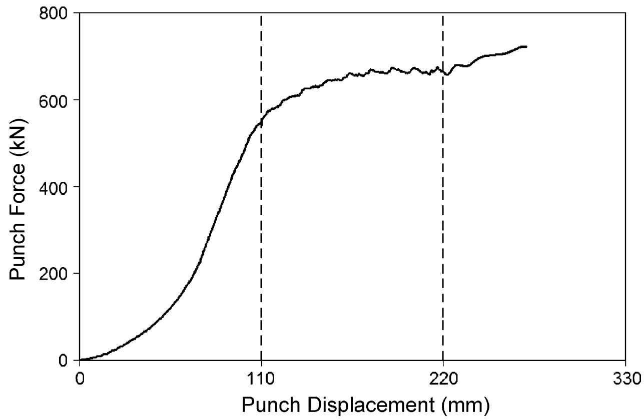

Fig. 4 – Punch force evolution in LPG bottle deep drawing.

an optimal constant force (OF) scheme may be utilized. In addition, linearly increasing (IncF) and decreasing (DecF) blank holder force schemes were also studied. Finally, to cater the design objectives of the part, a variable blank holder force scheme (VBHF & VBHF3P) is proposed. The VBHF schemes improve the quality of the formed part as demonstrated in the following sections.

The aim of the proposed variable blank holder force scheme is to apply a minimum blank holder force on the cup flange to just restrict the wrinkling tendency. The blank holder force is applied through a single rigid blank holder on the flange of the blank. In the variable blank holder force scheme, the drawing process is divided into three phases that are determined based on the analysis of the punch force evolution as shown in Fig. 4. The punch force increases until about 110 mm of punch displacement, beyond which the rate of increase reduces. When the punch reaches about 220 mm the punch force increases significantly. Generally, beyond this punch stroke the punch force drops due to the existence of large-scale plastic deformation. In the beginning of the forming process, as the punch force increases, a constant, low-blank holder force is applied. A lower initial blank holder force decreases the tendency of thinning in parts such as LPG bottles with large depth. Higher blank holder force in the initial stages restricts the flow into the die cavity and causes overall thinning at the end of deep-drawing process and necking in the vicinity of punch radius. As soon as the punch force attains saturation, starting from a higher value, the blank holder force is increased gradually at a rate just sufficient to restrain the flange from wrinkling. A high-blank holder force at the start of this phase restricts wrinkling due to high-compressive strain in circumferential or hoop direction accumulated during the first phase. In the third phase, when most blank has been drawn into the die cavity, the flange-blank holder contact area becomes smaller and hence a constant blank holder force may be sufficient to prevent wrinkling. Hence, the variable blank holder scheme may have three phases (VBHF3P) or just two phases (VBHF). In addition to the variable blank holder force scheme, controlling friction at specific location with high-frictional resistance augments the blank's formability. The blank flows through the die radius under tension with high-frictional resistance. Hence, reducing friction at this interface will improve the flow of material into the die cavity. A global Coulomb's friction coefficient of 0.14 was used. However, in VBHF scheme, at the die radius a lower value of 0.09 was used.

3. Results and discussion

3.1. *Punch force*

Generally, the thickness is unevenly distributed in the part after deep drawing. The thickness is uniform at the bottom face of the punch, least at the vertical surface and thicker at the flange area. In the vertical wall, especially the section near the base of the cup, wall thinning occurs due to stretching and large plastic deformation. In addition, large stresses are induced in the deformed blank when it passes through the die radius, due to bending and unbending. A portion of these stresses remains in the blank as residual stress because of the bending that occurred near the end of the deep-drawing process. Proper blank holder force and friction condition will reduce these tendencies thereby increasing the integrity of the part. In this study, a number of blank holder force schemes were studied to throw light on the deep-drawing process and to produce a defect free LPG bottle. In addition to blank holder force scheme, solid lubricant coating at the die radius enables a smoother material flow into the die cavity. Fig. 5 shows the punch force evolution for different blank holder force schemes. It varies depending on the applied blank holder force. High-blank holder force application (HF) requires high-punch force in order to form the blank, while a low-blank holder force application results in wrinkle formation. As the wrinkles develop and grows, the punch force requirement becomes erratic. The variable blank holder schemes (both VBHF3P and VBHF) results in a low-punch force requirement. VBHF3P needs marginally increased punch force after the first phase due to increased applied blank holder force (not shown due to indistinctness). The variable blank holder force scheme (VBHF), with two phases, requires least punch force as shown in the figure. Hence, an optimal blank holder force strategy is essential for less energy consumption and improved part quality.

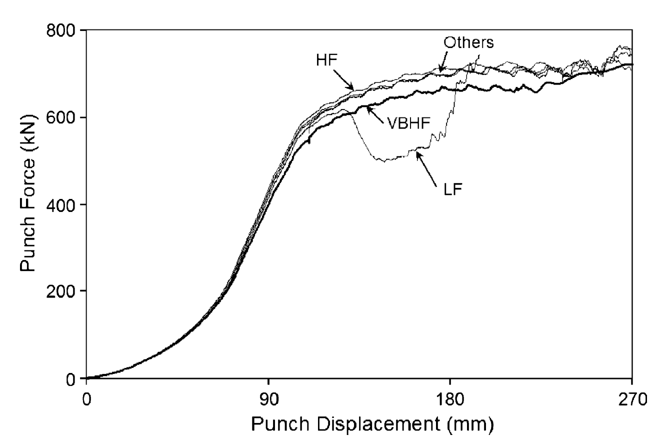

Fig. 5 – Punch force evolution for different blank holder force schemes.

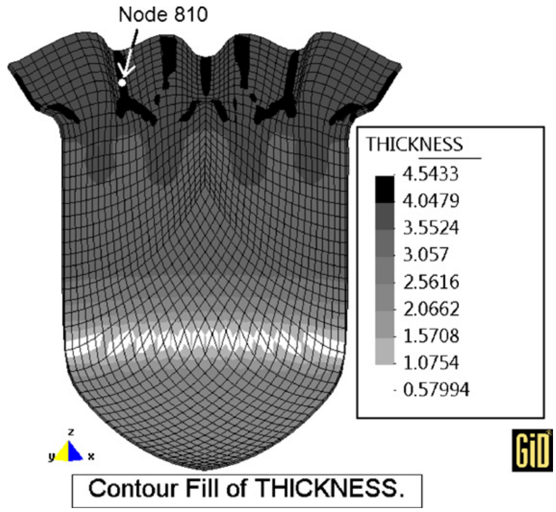

Fig. 6 – Wrinkling at flange area and tearing at punch radius due to low-blank holder force.

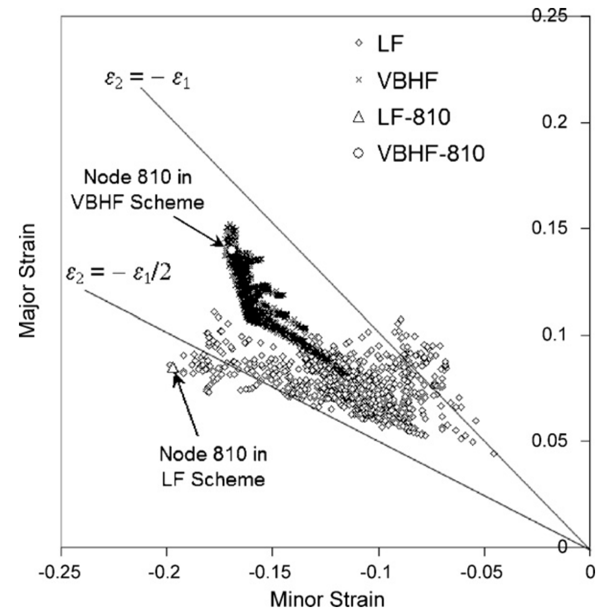

Fig. 7 – Partial forming limit diagram.

3.2. *Wrinkling*

Wrinkling and tearing are two major issues that induce irregularities in the formed part. Wrinkling is mainly caused by inadequate blank holder force and tearing is caused by excessive blank holder force. Wrinkling is a wavy condition obtained in the blank while drawing due to unbalanced compressive forces set up in the flange area. This study is intended to evolve a strategy that utilizes optimum blank holder force in order to improve the quality of the part. This can be achieved by using a blank holder force just above wrinkling threshold from the beginning of the deep-drawing process. The basis for this control is attained from the blank holder displacement. Fig. 6 shows the wrinkles formed at the flange area of the drawn cup. A low-blank holder force is sufficient to retain the blank in place during the initial stages of deep drawing. At about 110 mm of punch displacement, wrinkles are formed and develop thereafter. Utilising a low-blank holder force throughout deep-drawing process will result in the rejection of parts due to wrinkling at the flange area and tearing at the punch radius, as shown in figure.

Fig. 7 shows the partial forming limit diagram to elucidate wrinkling tendency while using low-blank holder force scheme. The plot includes nodes in the flange area. Other nodes are subjected to stress–strain states within process window and hence not included in the plot. One node (Node 810 shown in Fig. 6) is identified on the flange area to illustrate wrinkling tendency while using low-blank holder force scheme. When the strain ratio is below $\varepsilon_1 = -\varepsilon_2/2$ line, wrinkling occurs in the blank. When node 810 is subjected to low-blank holder force scheme, the strain ratio is below this line, while it is in the safe zone (above $\varepsilon_2 = -\varepsilon_1$ line) when subjected to VBHF scheme. This and the results discussed in previous sections clearly indicates that VBHF scheme is capable of producing high-quality parts compared to other blank holder force schemes.

Fig. 8 shows displacement of the blank holder during deep-drawing process during different blank holder force scheme. During deep drawing, the distance between the blank holder and the die surface increases depending on the applied scheme. When low-blank holder force scheme is applied, the increase is insignificant until about 120 mm. Thereafter, it increases drastically indicating the onset of wrinkles in flange area. When a decreasing blank holder force scheme is used, the distance increases drastically after 200 mm of punch displacement. This indicates that a higher blank holder force is essential to contain wrinkling, especially near the end of the deep-drawing process. However, an optimal blank holder displacement is observed while using the variable blank holder scheme.

Fig. 9 shows the blank holder displacements in other schemes that produced cups without wrinkles. Gradual increase in the distance between blank holder and die surface is observed in HF, IncF, and OF cases. In variable blank holder scheme (VBHF), the blank holder displaces sharply at the end of first phase owing to the low-blank holder force. Due to the change in the applied blank holder force at the beginning of the second phase, this distance reduces initially and

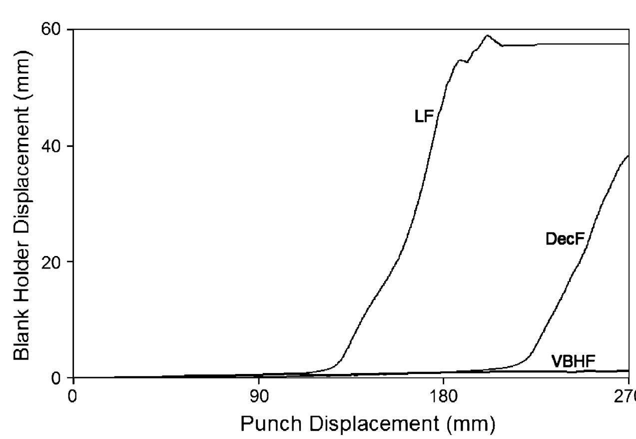

Fig. 8 – Comparative blank holder displacement for LF, DecF and VBHF schemes.

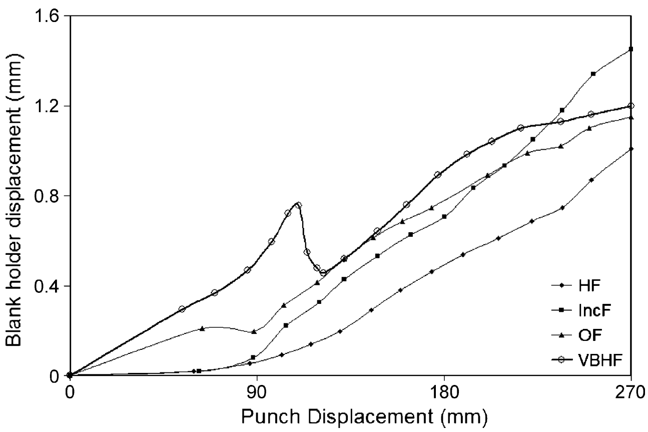

Fig. 9 – Comparative blank holder displacement for HF, IncF, OF and VBHF schemes.

increases later. The increase in the blank holder displacement is less in the final phase of deep drawing when the flange area is smaller. Except the initial stages, the displacement of the blank holder is mainly due to the thickening in the flange area. With the applied variable blank holder scheme, the maximum blank holder displacement is kept within 1.2 mm.

3.3. *Thickness distribution*

The main objective of the proposed scheme is to reduce thickness variation in the deep drawn part, i.e. to maximize the minimum thickness. Existence of thickness variation from the production stage may cause sudden rupture in the gas bottle if subjected to bumps, deformation, corrosion and other damaging mechanisms during service. Fig. 10 shows the blank draw-in after deep drawing to a depth of 270 mm. High-blank holder force limits the draw-in and hence results in a lower limiting drawing ratio (LDR). The proposed variable blank holder scheme resulted in improved LDR as shown in the figure. Due to increased draw-in, the flange area in the variable blank holder force scheme is less than that obtained from other blank holder force schemes.

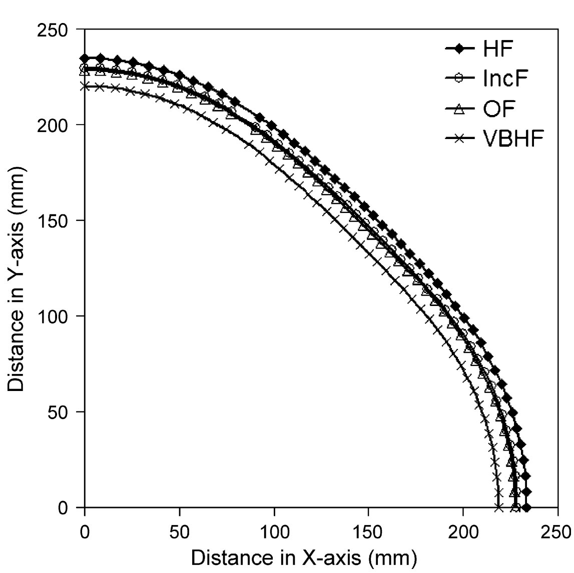

Fig. 10 – Draw-in in the blanks.

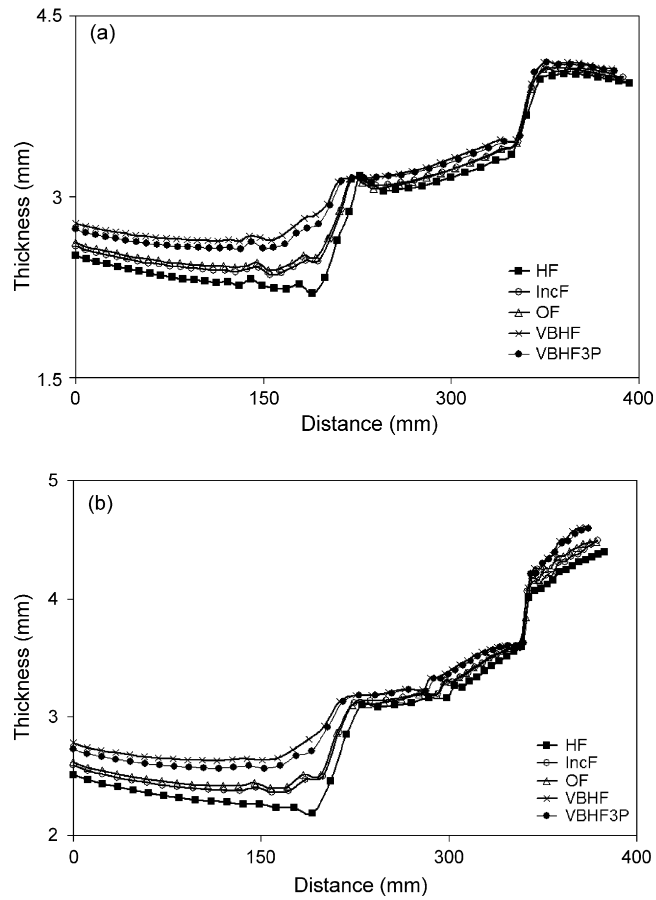

Fig. 11 – (a) Thickness variation along rolling direction (*OX*) and (b) thickness variation along diagonal direction (*XY*).

Fig. 11 shows the thickness variation in the deep drawn part, along the curvilinear lines of rolling direction (*OX*) and diagonal direction (*XY*), using different blank holder force schemes. Wall thinning occurs at the bottom of the cup wall and thickening occurs near the top and at the flange. Near the top of the cup section and at the flange, blank thickening occurs due to the friction at die-blank interface and the circumferential forces. Deviations in the strain distribution can be attributed to inaccuracy of Hill'48 yield model, mainly at equi-biaxial stress state. But, most thinning in the drawn part is observed around the bottom of cup wall and the punch radius where the stress state is different. High-blank holder force (HF) restricts material flow from the beginning of the process and hence the part is subjected to maximum thinning, as shown in Fig. 11(a). With a constant optimal force scheme (OF), thinning is reduced due to the lower force value. Increasing blank holder force scheme (IncF) produced similar results comparable to optimal force scheme. Due to higher applied blank holder force after first phase in VBHF3P scheme, marginally increased thinning is observed. Variable blank holder force scheme (VBHF) produced minimum thinning as shown in the figure. The difference between wall thickness and cup bottom thickness is minimized using variable blank holder scheme. The draw-in along diagonal direction is comparatively more than the rolling and transverse directions which leads to increased thickness at the flange as shown in Fig. 11(b).

In the proposed variable blank holder force scheme, more material flows into the die cavity during initial stages of forming. In addition, lower friction coefficient at the die radius enables smooth and uniform flow of material reducing thinning tendency. Maximum thinning is observed along the punch bottom face. The proposed strategy results in an improved thickness distribution and reduced thinning in the deep drawn part. The minimum thickness observed in the cup is 2.63 mm satisfying the design objective.

3.4. Stress–strain state

The residual stress present in the part after removing forming tools has significant influence on its service performance. In this specific application (LPG bottles), the part will be subjected to bumps, fatigue, corrosion, etc., during service. Residual stresses present during manufacture will render additional burden on the part. Fig. 12(a) shows the residual stress distribution in the part formed using optimal blank holder force scheme and Fig. 12(b) shows the distribution in the part formed using variable blank holder force scheme. The residual stress distribution in both part appear similar and close to zero stress in the useful portion of the cup. Marginal residual stress is observed at the punch radius. High-residual stress is observed at the die radius and flange area which will be trimmed subsequently for fabrication of the gas bottle.

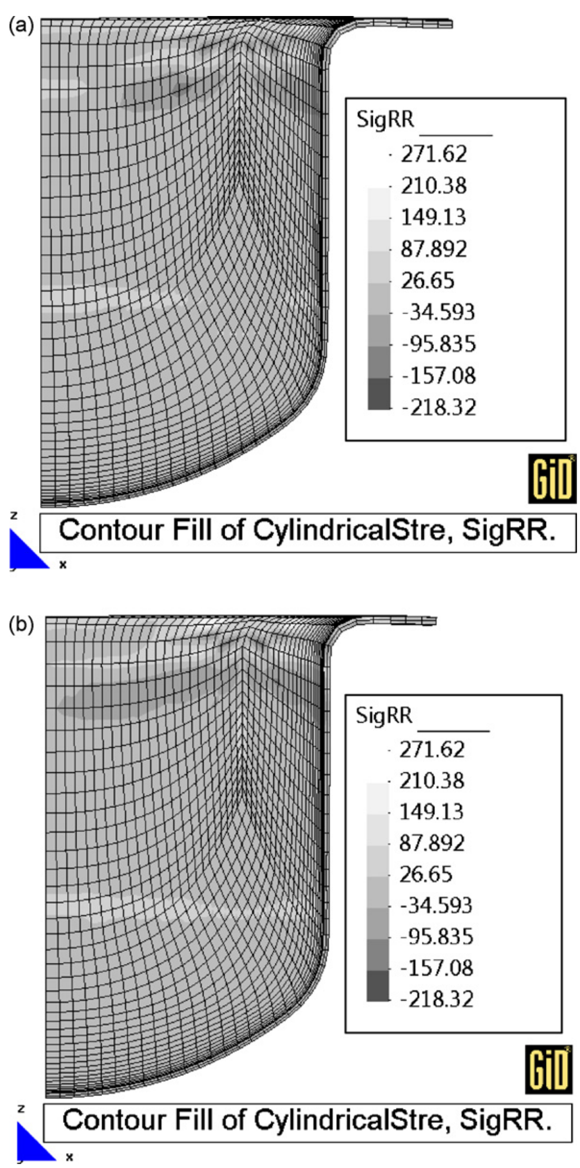

Fig. 12 – Residual stress distribution in part using (a) OF and (b) VBHF schemes.

4. Conclusions

Numerical results indicate that the proposed variable blank holder force and lubrication strategies can be used in the deep drawing of axi-symmetric cups, in particular the studied gas bottle example. A constant blank holder force scheme induces larger deformations in the initial stages of deep drawing leading to an increased thinning at the bottom of the cup, whereas, the proposed variable blank holder force scheme and friction condition reduces the thinning of the deep drawn part. A low-constant blank holder force in the initial stage prevents necking failure between punch and die radius. The magnitude of the blank holder force at initial stages of deep drawing plays a vital role in the thickness distribution in the drawn part. When the punch force remains constant, an increasing blank holder force restrains the wrinkling tendency and enables a smooth flow of material into the die cavity. In addition, localized variation in contact friction condition at the die radius enhances the flow of material. The proposed variable blank holder force scheme and friction condition resulted in an increased minimum thickness in the deep drawn part, expending relatively less energy in restraining the flange through the blank holder.

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