Numerical analysis of hydroforming process control using variable blankholder force

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Abstract. Hydroforming was developed to provide a cost effective means to produce relatively small quantities of drawn parts or parts with asymmetrical or irregular contours that are difficult to obtain by conventional stamping. This paper presents a study of hydroforming process with variable blankholder force in order to assure the parts quality. The main idea is to decompose the blankholder function of the elementary zone of the part contour corresponding to the linear and curvilinear zone. For each zone different blankholder force is applied in correlation with the hydrostatic pressure. A numerical analysis using finite element modelisation is performed considering different sets of blankholder forces and hydrostatic pressures, as process parameters. An optimum is determined in order to avoid parts defects (thickness reduction, wrinkles, fracture) for such types of parts.

1. Introduction

Sheet hydroforming is a process that consists of forming a blank into a certain shape by using a punch to mechanically press the blank into a pressure chamber filled with hydraulic fluid [1].

The process of sheet hydroforming offers several technological advantages for example higher deep drawing ratios, better geometrical accuracy and cost efficiency compared to conventional deep drawing processes. Additionally this technology is more suitable for deep drawing modern high strength steel or aluminium alloys which are utilized more and more in the automotive and aerospace industry [2].

Despite the advantages of this method, it has some limitations. Most research in robust process design focuses on problems with a single response but practical problems as sheet metal forming processes, often require the simultaneous improving of many quality characteristics (i.e. blank thinning and geometrical accuracy) and productivity considered as output parameters in the stage of process modeling.

Different researchers considers as input parameters the following process parameters:
- geometrical features within the tool design [3,4];
- fluid pressure path [5,6,7]; pressure path is the most important parameter for increasing the drawing ratio in HDD; finding the appropriate fluid pressure-punch stroke path while avoiding rupture and wrinkling instabilities is a critical and difficult step;
- time dependent blankholder force and the fluid pressure [8]
- blankholder force variation through the stroke and slide velocity [9];
- blankholder force variation through the stroke [10]
The studies performed for the optimization and control of the hydroforming process used both experimental and numerical methods. Finite element method is very common and the results obtained in this way can be exploited using ANOVA, neural network method, reduced order method [11,12] in order to obtain a process model with short time response or able to predict its results (quality characteristics of the piece and process productivity) [1].

During the deformation process the material flow into the die it is higher in the linear zones of the contour than in the corners zones. Considering the similarity with conventional deep drawing process using composed blankholder force [13-15] this paper propose a method to compensate the unequal material flow. This method consists in the use of a segmented blankholder with different value of the applied force corresponding to the different areas of the blank.

The blankholder forces or pressures values in a deep drawing or sheet hydroforming process determines the final properties and the quality of the formed part. If the loads applied on the blankholder are too low and the material flows too quickly, the blank will wrinkle, but if there are very high blankholder loads, the material flow may be slowed and that may cause the formed part to break.

For parts that require multiple different loads to be applied in different areas of the blankholder to improve their formability, there are methods like using a segmented blankholder or using a multi-point cushion system. These methods allow the possibility of using different loads on different locations of the blankholder for the areas of the blank where there needs to be more or less pressure (or force) than the other areas to prevent wrinkling, thinning or a possible rupture of the formed part [16].

Forming limit diagrams (FLD) are used to determine a material’s formability to be able to predict if there are risks of necking (for values higher than the FLC) or breaking (for values higher than the FFL) of a part made from that material. The FLD are formed by using the maximum principal in-plane strains $\varepsilon_1$, named major strains and the minimum principal in-plane strains $\varepsilon_2$, named minor strains, that can be obtained either experimentally or numerically [23-26].

This paper intends to study the relation between the different applied pressures on the different areas of a segmented blankholder and hydrostatic pressure toward the formability of a hydroformed square part by using the finite element software Abaqus. The formability is appreciated by considering the level of thickness, stresses, strain variation and fracture using the FLD.

2. FEM Model
A series of finite element analyses and experiments of a conventional deep drawing process for forming square parts have been performed and the results showed a good agreement between the simulations and the experiments [18].

The researches presented in this paper can be seen as a continuation of those tests and they consist in a numerical analysis of a hydroforming process considering a case study, presented in figure 1 [18]. The hydroforming process of a rectangular part obtained from an aluminum blank is modelled using Abaqus software. The hydroforming process model contains: the blank, the blankholder, the punch and the die that also acts as a pressure chamber (figure 3).

The main dimensions of the modeled assembly components are presented below. Similar assembly was used and analysed by Hama [17] in their researches.

In figures 2 and 4 the following notations have been made:

- Lp, Lbh, Lb, Ld, Lf – the lengths of the punch, blankholder, blank, die chamber and formed part, respectively
- Wp, Wbh, Wb, Wd, Wf – the widths of the punch, blankholder, blank, die chamber and formed part
- hp, hd, hf – the heights of the punch, die chamber and formed part
- tbh, tb – the thicknesses of the blankholder and blank
- rp, rbh, rb, rd, rf – the radii of the punch, blankholder, blank, die chamber and formed part

The numerical values of all model components and formed part are presented in the table 1.
Figure 1. The final dimensions of the formed part [18].

Figure 2. Dimensions of the blank.

Figure 3. Assembly Components.

Figure 4. Dimensions of the sectioned assembly.

Figure 5. Values of pressures $p_1$, $p_2$ applied on the blankholder and of the hydrostatic pressure $p$.

Table 1. The dimensions of the modeled components.

| Components   | Length [mm] | Width [mm] | Height / Thickness [mm] | Radius [mm] |
|--------------|-------------|------------|-------------------------|-------------|
| Punch        | $L_p=78$    | $W_p=48$   | $h_p=45$                | $r_p=5$     |
| Blank holder | $L_{bh}=140$| $W_{bh}=110$| $t_{bh}=1$              | $r_{bh}=5$  |
| Blank        | $L_b=124$   | $W_b=98$   | $t_b=1$                 | $r_b=49$    |
| Die chamber  | $L_d=80$    | $W_d=50$   | $h_d=20$                | $r_d=5$     |
| Formed Part  | $L_f=80$    | $W_f=50$   | $h_f=35$                | $r_f=5$     |
The components were modeled using shell elements (homogenous, thickness integration rule: Simpson, thickness integration points: 5) and the following properties:
- the blank was modeled as a 3D deformable shell with 1 mm thickness; the material assigned was aluminum and plastic properties were added (strength coefficient \( K=352.14 \), Young modulus \( E=61370 \) Mpa, yield strength \( \sigma_0=173 \) Mpa, strain hardening exponent \( n=0.163 \), tensile strength \( \sigma_r=262 \) Mpa, Poisson ratio 0.3). The yield criterion used was Barlat ’89 and the hardening law was Swift [26];
- the blankholder was modeled as a 3D deformable shell with 2 mm in thickness and assigned material – steel;
- the punch and die were each modeled as a 3D discrete rigid body.

Loads (figure 5):
- the blankholder was divided in 8 areas corresponding to the linear and curvilinear zone of the part’s contour; two different pressure values with a linear variation (starting from 0 to the applied value) were applied on these areas: pressure \( p_1 \) on the four linear zones of part’s contour and pressure \( p_2 \) for each of the four corners (curvilinear zones of part’s contour). The pressures values were taken from [17, 19].
- the hydrostatic pressure (p) of the hydroforming liquid, also with a linear variation, was defined without any extra initial pressure, without overcharging [17] and was applied on the bottom face of the blank. The pressure value was taken from [17, 19, 20].

The boundary conditions were:
- the die was considered fixed body (all degrees of freedom were zero);
- the punch had a translation on the z axis and a velocity was applied along this; all other degrees of freedom was blocked.
- The clearance between the die and the punch was 1t.

3. Numerical Simulation of Sheet Hydroforming
The finite element analysis of the hydroforming process of the rectangular part was carried considering as inputs the blankholder pressure in different areas and the hydrostatic pressure. Ten sets of values were prepared (table 2). The hydrostatic pressures were applied taken in account the avoidance of the leakage phenomenon. This phenomenon wasn’t numerically studied in this paper, treating the problem in a classic way.

| Data set | Crt. No. | \( p \) [Mpa] | \( p_1 \) [Mpa] | \( p_2 \) [Mpa] | \( t_{\text{initial}} \) [mm] | \( t_{\text{min}} \) [mm] | \( t_{\text{max}} \) [mm] |
|----------|----------|---------------|---------------|---------------|----------------|----------------|----------------|
| I.       | 1        | 4             | 7             | 7             | 1              | 0.891          | 1.450          |
|          | 2        | 5             | 7             | 7             | 1              | 0.891          | 1.447          |
|          | 3        | 6             | 7             | 7             | 1              | 0.891          | 1.453          |
| II.      | 1        | 5             | 7             | 8             | 1              | 0.890          | 1.447          |
|          | 2        | 6             | 7             | 8             | 1              | 0.891          | 1.449          |
| III.     | 1        | 5             | 8             | 7             | 1              | 0.891          | 1.450          |
|          | 2        | 6             | 8             | 7             | 1              | 0.891          | 1.450          |
| IV.      | 1        | 5             | 9             | 7             | 1              | 0.892          | 1.444          |
|          | 2        | 6             | 9             | 7             | 1              | 0.892          | 1.448          |
| V.       | 1        | 25            | 26            | 30            | 1              | 0.874          | 1.585          |
| VI.      | 1        | 25            | 30            | 26            | 1              | 0.873          | 1.545          |
| VII.     | 1        | 30            | 31            | 35            | 1              | 0.874          | 1.753          |
| VIII.    | 1        | 30            | 35            | 31            | 1              | 0.872          | 1.669          |
| IX.      | 1        | 50            | 51            | 55            | 1              | 0.865          | 2.577          |
| X.       | 1        | 50            | 55            | 51            | 1              | 0.866          | 2.378          |
For a global analysis of the quality assurance, the output parameter of the process was considered the thickness variation [21].

The first set has 3 different hydrostatic pressures and the blankholder pressure has the same value on the whole blankholder, in all 3 cases, acting as a rigid plate. The next 3 sets of data have only 2 different hydrostatic pressures each, while either the first or the second blankholder pressure is different than the first set.

The thickness values from table 2 can be observed in all the cases in the same locations: the minimum thickness value is in the bottom corner and the maximum value is in the top area of the formed part, at the contact zone between the linear and corner edges of the part (figure 8).

Because the differences of the first data sets results were small in terms of thickness variations, additional, higher values for the blankholders and hydrostatic pressures were also chosen, cases V-X from table 2.

For a detailed analysis of the process, two series of 20 points were picked by nodes, for each data set, in order to observe the evolution from the bottom to the top of some output parameters of the formed part. The first series of points were chosen from a line of the mesh in the TD of the formed part (figure 6.a). For the other series, the part was split diagonally, in order to obtain a reference line to help with picking points from the corner of the formed part (figure 6.b). The starting point was the same for both cases, in the center of the bottom of the formed part.

The output parameters that were observed in this case were the thickness of the formed part, the equivalent plastic strain, the Von Mises stress and the Cauchy stress tensor components $\sigma_{11}$ and $\sigma_{22}$.

![Figure 6. Measured points.](image)

4. Results and discussion
Several studies considered that the optimum of the process regarding the quality of the part should be established considering the following aspects: i) the formability of the part (characterized by the capacity of the process to avoid the wrinkling due to excessive compression and tearing because of high local stress that cause thinning and failure of the material); ii) dimensional accuracy (springback caused by elastic recovery); iii) consistency (representing the minimization of dimensional variations due to the variation of different parameters as lubrication, material properties and thickness). The close connection between the control of the stress state in the material during the process and the quality of the obtained piece is obvious. This is why, the critical zones of the part, from the point of view of stress state, were identified (figure 7). These zones are:

- Critical zone 1 represents the areas where the fracture of the material can appear due to: i) the equivalent von Mises stress exceeding tensile strength of the material, or ii) the biaxial tension stress state i.e. on the bottom piece area; both of these stress states determine a decrease in the value of the material thickness below the accepted value.
- Critical zone 2 represents the area where stress state is type tension+compression with tension dominance, determining wrinkles after the process, due to the springback.
Critical zone 3 represents the area where the stress state is type tension+compression with compression dominance determining wrinkles during the process. It can be observed that the critical zone are characterized by the stress state in the material, especially the value of the equivalent von Mises stress and Cauchy stresses tensor components, $\sigma_{11}$ and $\sigma_{22}$. $\sigma_{11}$ is the direct stress in the RD and $\sigma_{22}$ is the direct stress in the TD [22].

**Figure 7.** The minimum and maximum thickness values of a hydroformed part.

**Figure 8.** Critical zones of the hydroformed part.

After extracting the values of the thickness, the equivalent plastic strain, Von Misses stress and Cauchy stress tensor components $\sigma_{11}$ and $\sigma_{22}$ for the two series of 20 points, for each data set, the results were represented as graphs (figures 9 – 16). The graphs show the evolution of each considered output parameter for 3 zones: the bottom zone (points 1-5), the radius zone (points 6-10) and the wall zone of the formed part (points 11-20). Also in these graphs are represented the values of the first data set.

**4.1. Thickness variation**

The thickness of the formed part has small variations for the cases I – IV, both in the longer plane zone and in the corner sections of the part. The thickness along the TD has variations of 0.1 mm, plus or minus, between cases, meaning that the thickness results are very similar in this area for the first cases set. The cases V – X show more thinning than the first cases set, starting from the radius zone. In the wall zone there is a higher thickness in the cases IX and X, compared to the other cases.

The worst along the TD is the one from the data set X with a minimum value of 0.94 mm and a maximum value of 1.04 mm (figure 10). The cases II 1, II 2 and III 2 have the best thickness variations.

**Figure 9.** The thickness values from the points measured along the TD of the formed part.
The best thickness situation from the points that were chosen for the corner section (figure 10), can be seen in the case III2, that has a maximum thickness of 1.21 mm and on the opposite side is case IX with a maximum thickness of 1.29 mm, meaning that there is a bigger accumulation of material here than in the other cases. In all the cases there is a significant thinning at the bottom corner section with a value of 0.89 mm.

It can be concluded that the applied pressures have similar plots toward the thickness variations, both along the TD and corner zone. It is seen that the numerical simulations predict localized thinning around the punch radius, a limited, and uniform, straining at the bottom of the part, as well as the wall-thickening along and around the part edge, more pronounced in the corner zones [27, 28, 29]. The ears appears in these zones.

4.2. The equivalent plastic strain variation
Small variations can also be seen for the values of the equivalent plastic strain for the cases I – IV. In the along the TD of the formed part (figure 11), the maximum value is 0.37 for the case V. The lowest maximum value of 0.29 can be observed in the cases IV1 and IV2.

In the corner section, between most of the data sets there are only small variations, with the exception of the data sets IX and X, that have significant differences starting from the middle of the wall zone of the formed part. The biggest differences between all the cases can be seen at point 20, where the highest value is 0.73 in the case IX and the lowest value is 0.32 for the cases II – IV (figure 12).

It can be concluded that the applied pressures have similar plots toward the equivalent plastic strain variation, both along the TD and corner zone. It can be seen that the bottom of the parts develop
limited amount of strain in comparison to the walls, which experience strains beyond the limit of uniform elongation in uniaxial tension [27, 28, 29].

Figure 12. The equivalent plastic strain values from the points measured in the corner section of the formed part.

4.3. Von Mises stress variation

In the case of the Von Mises stress, the curves have bigger variations of values, but the shapes of these curves are similar between the cases I – IV. The cases IX and X have some significant differences compared to all the other cases.

The highest Von Mises stress value along the TD of the formed part was 448.29 MPa for the case IX at point 18, where the cases I – VIII have drops. The case I 1 has overall lower values than the other cases with a minimum of 80.13 MPa and a maximum of 396.98 MPa (figure 13).

Figure 13. Von Mises stress values from the points measured along the TD of the formed part.

For the corner section of the formed part, the most noticeable differences can be observed in the cases V – X, especially considering the fact that the cases IX and X have lower stress values in the radius zone and a few points from the wall zone. The highest Von Mises stress value is 531.49 MPa for the case IX, while the best case is II 2 with a maximum value of 507.85 MPa (figure 14).

The process simulation stopped before the hydroforming process was completed, in the cases IX and X. The finite element simulations with hydrostatic pressures of 50 MPa stopped before the full stroke of the punch, due to the large value of the equivalent von Mises stress. This situation is due to the wrinkles appearance in the top corner zones, blocking the flow of the material into the die. The
fracture can appear in the critical zone 1. It can be concluded that the applied pressures have small influence toward the Von Mises stress variation, both along the TD and in corner zone.

Figure 14. Von Mises stress values from the points measured in the corner section of the formed part.

4.4. Variation of $\sigma_{11}$ and $\sigma_{22}$ stresses
The graphs for the $\sigma_{11}$ and $\sigma_{22}$ stresses (figures 15-16) will be used to show what causes the high Von Mises values at the last few points of the corner section especially.

Figure 15. $\sigma_{11}$ stress values from the points measured along the TD of the formed part.

Figure 16. $\sigma_{22}$ stress values from the points measured along the TD of the formed part.
For the TD of the formed part, the cases I - IV have similar $\sigma_{11}$ (figure 15) and $\sigma_{22}$ (figure 16) stress curves, but the cases V – X are very different in the bottom zone and the cases IX and X are also different in the wall zone. The minimum value is in the case X for both stresses, near the radius zone of the formed part: $\sigma_{11} = -165.45$ MPa and $\sigma_{22} = -446.11$ MPa. The maximum $\sigma_{11}$ stress value is 304.32 MPa at the bottom of the part in the case X, and the maximum $\sigma_{22}$ stress value is 490.23 MPa also in the case X, near the top of the part.

$\sigma_{11}$ and $\sigma_{22}$ stresses are also similar for all the I – IV cases for the corner section, except the cases IX and X. For $\sigma_{11}$ stress, the maximum value is 495.63 MPa in the case X and the minimum value is -464.53 MPa in the case IX. $\sigma_{22}$ graph has a maximum of 462.88 MPa in the case IX and a minimum of -467.9 MPa in the case X.

The fact that both graphs show at the top corner of the formed part, point 20, decreasing values compared to the previous points for most of the cases and even compression values for the cases V – X, means that the material flow is slowed down in that area and that is the reason that there are very high Von Mises stress values near the same area.

The ratio $\sigma_{22}/\sigma_{11}$ shows a very high minimum value of -863.36 at point 16 in the case II 1 along the TD of the formed part, while in the corner section, in the same case – II 1, there is the highest maximum value of 113.44 at point 20. The lowest minimum value in the corner section is -51.46 at point 1 in the case VI. The positive values for the corner section are very small, the highest being 5.72 at point 20 in the case X.

4.5. FLD analysis

For the cases that were analyzed above, the major strain $\varepsilon_1$ and the minor strain $\varepsilon_2$ values were also extracted from the simulations to be able to compare them with the FLC of the material [26]. In figure 17, for case I 1 and figure 18, for the case III 1, it can be seen that most points are in the tension/compression side [23], but there are a few points where the strain values of the formed part overlap the FLC values, meaning that there are some areas where there is a small risk of necking. The cases I – IV show similar results.

![Figure 17. FLC comparison for the case I 1.](image)

In the case VI there are points that are clearly over the FLC values, meaning that there is necking and a higher risk of fracture, as can be seen in figure 19.
5. Conclusions
The study analyse the influence of the hydroforming pressure $p$ and $p_1$ and $p_2$, blankholder pressures applied to different areas of the blank in order to analyses the quality of hydroforming part. The study revealed:

- Good results are obtained when the pressure $p_1$ applied by the blankholder on the linear areas of the blank is larger than the pressure $p_2$ applied by the blankholder on the curvilinear areas of the blank, for the same value of hydroforming pressure. The pressure $p_1$ lowers the material flow on the die in the linear areas so the material flow on the entire contour it becomes more uniform.

- From the data sets I – IV, the best overall results can be seen in the case III 2, that had the blankholder pressures $p_1=8$ MPa, $p_2=7$ MPa and the hydroforming pressure $p=6$ MPa and the worst results were in the case IV 2 with $p_1=9$ MPa, $p_2=7$ MPa, $p=6$ MPa.

- At higher pressures (data sets V – X), it was observed that some tests failed near the end. The failure occurred when the material stopped flowing because the applied pressures were too high.

- The best case between V–X was the case V that had the input parameters $p_1=26$ MPa, $p_2=30$ MPa, $p=25$ MPa and the two worst cases are: case IX with $p_1=51$ MPa, $p_2=55$ MPa, $p=50$ MPa and case X with $p_1=55$ MPa, $p_2=51$ MPa, $p=50$ MPa, that had the overall worst results.

- Comparing the case III 2 with the case V it results the following: the minimum value of the thickness is 0.891 in the case III 2 and 0.874 in the case V; the maximum value of Von Mises stress is 519.5 MPa in the case III 2 and 545.4 MPa in the case V; the equivalent plastic strain

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**Figure 18.** FLC comparison for the case III 1.

**Figure 19.** FLC comparison for the case VI.
has the maximum value of 1.27 in the case III 2 and 1.28 in the case V, showing the assurance of conditions for achieving a higher degree of deformation. Analysing these values, it results that the best case between all that were studied is the case III 2.

- The quality of hydroformed part is well expressed by the stress (equivalent von Mises stress and components $\sigma_{11}$ and $\sigma_{22}$ of Cauchy stress tensor) evolution in the critical zones of the part, the minimum value of the thickness and the maximum value of the equivalent plastic strain.

- The applied pressures have similar plots toward the thickness, equivalent plastic strain and Von Mises variation, both along the TD and in the corner zone.

- Because in the top corners of the formed part there was an accumulation of material and the thickness had a very high value there compared to the rest of the part, those areas were trimmed at the end, similarly to what happens in reality. By removing the top corner areas the thickness distribution can be observed more accurately, as seen in figure 20 for the case I 1. The last four points from the 20 that were picked in the corner section previously are removed in this situation, the 16th point being the last one remaining after trimming. By trimming the part, most of the maximum values of stresses and thickness variation at the top areas are eliminated which leads to obtain a sound product.

The next step of the research is to perform:
- numerical studies regarding the process optimization, considering as inputs both design and process parameters and as outputs parameters the spingback values and degree of thinness;
- experimental tests to compare the obtained results with the ones from the finite element analysis;
- FEM simulations of the leakage phenomenon.

![Thickness variation comparison](image)

**Figure 20.** The thickness variation of the formed part.

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