Research on the optimization of stress relief holes applied in blanks used for body-in-white stamping parts with complex asymmetrical shapes

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Abstract. Increasing the degree of deformation when stamping body-in-white parts with complex asymmetrical shapes can be achieved by optimizing the discharge holes in the flange of the blank. For this purpose, the numerical simulation of the deep-drawing process with finite element is used. Considering the circular shape of the unloading hole, the expanded shape of this hole is determined using the FEM, taking into account the safety limit given by the final shape of the stamped part. To check that the deformation that occurs at the edge of the expanded hole not cause cracks in the part the area with deformations whose values exceed the permissible limit is delimited. The arc that stretches this area along the contour of the expanded hole is divided into a convenient number of equal segments. The points at the end of each segment are then translated on the edge of unloading hole by measuring the distances between these points on the expanded blank hole. Using a mathematical modelling of the allocated points on the contour of the unloading orifice, the corrected shape of this orifice is determined, which is perforated in the flat blank.

1. Introduction
In body parts manufacturing stress relief holes applied in blanks are used for deep drawn parts with complex shapes to allow increasing of deformation degree. Often without the use of such holes the parts are infeasible and has cracks. Examples of parts that need presence of such holes are body side outer, door inner, trunk lid inner and other symmetrically or different parts that have been connected in the same die.

If there are two parts in the same blank the size of the deformed hole in the space between parts influences blank dimension and material flow ratio. Always we try to optimize this flow ratio who is one important parameter of process performance.

Figure 1 shows the case of stamping two symmetrical pieces, arranged face to face, having the longitudinal plane of the die as a plane of symmetry.

The parts are represented in blue, with the filled surface of the holes in red. It can also see in beige the surface of the die on which the following elements are highlighted: the drawbead (green surface), the red line representing the die entry line and the blue line corresponding to the boundary of the part.

The surface between the two parts is scrap and is used to place a hole to eliminate internal stresses.
The blank shape is shown by dark blue dashed lines.

To avoid any crack propagation on the part we must predict the risk of cracks on deformed hole boundary. FEM simulation could be used for this [10]. Also using FEM simulation, the position, dimension and shape of the holes could be evaluated.

One of the most used FEM simulation program in sheet metal forming is Autoform [11]. The robustness of the results obtained with Autoform allows to use the simulated geometry directly to the die machining and then the validation is done at try-out where the results obtained theoretically through simulation are checked. For this reason, are very important to start the try-out with one blank who has a corrected and tested hole.

The originality of this work consists in finding a method to apply some corrections on the shape of the initial hole in order to eliminate the risk of cracks on the boundary of the expanded boundary hole after deformation that would propagate on the part causing to reject it. The purpose is to identify some rules to establish position, dimension and shape of the hole for reducing the number of simulation iterations which require a lot of time. Autoform and an original program for optimize the hole geometry are used.

2. Degree of deformation analysis

In deep drawing of complex body parts its difficult to define a global degree of deformation, because this differs from region to region. So, this parameter is defined in sections with high degree of deformations.

For the case presented in figure 1, the degree of deformation of the blank in two sections, longitudinal and transversal, was analyzed after completely deformation of the blank.

The initial dimensions of the blank, shown in yellow dotted line in figure 2, are:

\[ L_{1 \text{ ini}} = 1370 \text{ mm} \] the cross section (red curve)
\[ L_{2 \text{ ini}} = 1195 \text{ mm} \] the longitudinal section (blue curve).

At the end of the stamping stroke, highlighted in figure 3, the deformed blank has the following dimensions measured in the two sections:

\[ L_{1 \text{ fin}} = 1825 \text{ mm} \] the cross section (red curve)
\[ L_{2 \text{ fin}} = 1468 \text{ mm} \] the longitudinal section (blue curve).

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**Figure 1.** Parts arrangement in the die.
The degree of deformation for the complete stroke is:

\[ \varepsilon_{\text{trans}} = \frac{1825-1370}{1370} = 33.21\% \]  
(1)

\[ \varepsilon_{\text{long}} = \frac{1468-1195}{1195} = 22.84\% \]  
(2)

These values are used only to identify the localization of the biggest theoretical deformation and to choose first hole position for following iterations.

For each material there is a file charged in AUTOFORM simulation program who give the information like hardening curve, anisotropy values, yield surface model and forming limit curve [9]. These values is one average of values from different suppliers to assure that simulation results are the same like in reality.

The maximum allowed limit for the material is 29% according to [8] and is available for pure traction (\(\varepsilon_2 = 0\)) and it’s correspond of intersection between forming limit curve and y-coordinate axis. To have robust results is used one safety limit of 20% below FLC curve.

From the analysis of the deformation behavior of the blank, it was found that the first breaking primer indicated with red arrows appears 42.7 mm before the end of the stroke (figure 4).

It was noticed that the initialization of the rupture is in the area where we have the counter-drawing on the piece. For this reason, it is necessary to add a technological stress relief hole between the two parts in the scrap area (figure 5). In the initial case we have draw-in only for external boundary of the blank and we need to reduce internal tensions between those die radii.

By adding a hole internal tension are removed and hole boundary are free to expand and finally reduce tensions in areas where are cracks.
3. Deformation state analysis around the hole
A simulation was performed with a blank containing a 200 mm diameter hole. The presence of an area with a risk of rupture identified by the yellow color on the boundary of the deformed hole was observed and the position of these finite elements was determined on the FLD diagram (figure 6).

![Figure 6. The position of the elements on the diagram.](image6)

The network of colored triangular finite elements according to the corresponding area of the FLD and the main directions of deformation which are indicated by red for expansion or blue arrows for compression are shown in figure 7 and 8.

After selecting a finite element on the part, its position on the deformation limit diagram is highlighted by a dot and the values of the degree of deformation in the three directions are indicated in figure 8.

For example, the following values were highlighted for the specified item:

\[
\begin{align*}
\epsilon_1 &= 0.529 \\
\epsilon_2 &= -0.297 \\
\epsilon_3 &= -0.232.
\end{align*}
\]

![Figure 7. Highlighting the directions of deformation.](image7)  
![Figure 8. The position of a finite element on the FLD diagram.](image8)

It was observed that the elements on the contour of the hole are deformed in the plane in two directions. Tensile stress is present on the tangential direction to the contour, and compression stress is present on the perpendicular direction (in the radial direction).

This position of elements on FLD diagram shown increasing of deformation on traction, over the limit of pure expansion, because elements are subject of compression on the other two directions.

Finite elements have been numbered on contour of the hole as shown in figure 10. In figure 9 are presented deformations in graphical form associated with the table.
Figure 11. Components of strains on the periphery of the hole [3].

In paper [3] have shown three types of deformations on a blank which include a hole subject to expansion: deformations in the circumferential direction on the periphery of the hole $\epsilon_\theta$, in the radial direction $\epsilon_r$ and in the thickness direction of the material $\epsilon_t$, figure 11.

It is considered that the deformation of the radial expansion that occurs in the case of holes deformation may be comparable with that of the tensile test specimen case.

In the case of perforated holes, the degree of expansion is lower because during processing, plastic deformations are generated along the edge of the hole, which are accompanied by local hardening, microcracks and burrs. However, it is preferable to use this process because it is less expensive and has a higher productivity than the other methods.

The degree of expansion of the hole, $\lambda$, according to ISO 16630-2009 is determined by the relation:

$$\lambda = \frac{D_f - D_0}{D_0} \cdot 100 \% \quad (3)$$

where $D_f$ is the final diameter of the hole; $D_0$ - the initial diameter of the hole.

The paper [1] highlighted the criterion of maximum edge tension for the analysis of rupture on the contour of the hole. Maximum extension of the edge of the opening ($\epsilon_{max}$) is equivalent to the degree of expansion of the hole.

$$\epsilon_{max} = \lambda \% \quad (4)$$

The maximum deformations are calculated with the relation:

$$\epsilon_{max} = \ln \left(1 + \frac{\lambda}{100}\right) \quad (5)$$
This criterion can be used to estimate the occurrence of cracks on the edge of the hole, is compatible with the formability simulation using CAE applications and may have limited use in the analysis of deformed grid pattern marked on parts. In this paper is considered that the state of stress at the edge of a circular hole is approximately uniaxial tensile.

Starting from the equation of the degree of expansion of a hole we can write:

\[
\lambda = \frac{D_f D_0}{D_0} - 100 = \frac{\pi(D_f D_0)}{\pi D_0} - 100 = \frac{L_f L_0}{L_0} \cdot 100
\]

where \(L_f\) is the length of the diameter circle \(D_f\) and \(L_0\) is the length of the diameter circle \(D_0\).

It was considered that for the irregular holes the two initial and deformed lengths of the hole can be used, respectively. The deformed contour was divided into segments according to the deformations resulting from the simulation, called \(L_{fi}\), where \(i\) corresponds to the number of segments. By determining the position of the points on the initial contour, the corresponding \(L_{0i}\) segment is determined.

Equation (6) becomes:

\[
\lambda = \frac{L_f - L_0}{L_0} = \frac{\sum_{i=1}^{n} L_{fi}}{\sum_{i=1}^{n} L_{0i}}
\]

Figure 12. The result of the correction by reducing the radius. Figure 13. The result of correction by increasing the radius.

Basically, in order to eliminate the thinning on the edge of the hole, the degree of deformation of the respective segment must be equal to the maximum tensile deformation. For this, the length of the segment subjected to expansion was modified by increasing it while maintaining the position of the points that delimit the segment. Tests have shown that the shape leading to the reduction of the deformation of the hole is obtained by changing the segment to the inside of the hole according to figure 12.

4. Analysis of the trajectories of the points on the contour of the hole during the deformation

Figure 14. Deformation of the hole.
The Autoform software dynamically shows the change in the shape and position of the punch made in the semi-finished product on the entire drawing stroke. At the end of the drawing stroke, the direction of the material flow is indicated by lines and these values can be measured. The values of the minimum hole expansion of 6.73 mm and a maximum of 64.96 mm are indicated. The values can be measured both in the direction of material flow and perpendicular to the contour of the initial blank (figure 14).

Two points were chosen on the expanded hole delimiting the area in which the thin limit was reached at the final stroke (marked with E and F). The punch is then retracted to the stroke 24.42 mm before the bottom dead center when the first finite element on the contour of the hole reaches the limit of thinning. We note the position of the points chosen at this stroke with C and D. Then the punch is withdrawn at the beginning of the stamping operation when the blank is undeformed. I noted these points with A and B.

5. Working method for hole correction

5.1 Graphic determination of the profile

1. After the first simulation, the areas where the finite elements on the contour of the hole exceeded the safety limit were identified
2. Two points on the contour delimiting this area were chosen (figure 15) and the length of the deformed curve was identified. The deformed curve and the 2 points in (.igs) format were exported and overlapped on the punch surface.
3. The punch was moved until the first element that reaches the safety limit appeared to identify the position of the two points on the deformed hole. These elements were also exported and designed on the surface of the punch.
4. The curve of the deformed semi-finished hole was designed under the action of its own weight as well as the two points.

Figure 16 shows the curves mentioned above:
- the deformed contour is indicated by the color blue;
- the contour deformed when the first element reaches the safety limit with green;
- the contour deformed under its own weight by the magenta color.
5. The system of axes was chosen with origin in the center of the circle corresponding to the hole in the blank, all the coordinates of the points on the three curves being measured in relation to it.

6. Three curve lengths measured on the punch surface shown in figure 17 were identified:
   - the first corresponds to the initial orifice deformed under its own weight AB;
   - the second corresponds to boundary of the hole when the first element reaches the safety limit CD;
   - the third, EF, which corresponds to the contour of the hole at the end of the stroke.

7. The length of the CD corresponds to the maximum deformed segment without breaking.

8. Until the end of the operation we have another stroke of 24.42 mm, so additional deformation.

9. To allow further deformation without breaking, the length of the segment AB must be longer.

10. The curve was drawn, brown color, which was then connected by tangents to the initial profile. The length of the sinusoid, $L_{\text{sin}}$, was calculated with the relation:

$$L_{\text{sin}} = L_{AB} + L_{EF} - L_{CD}$$

where: $L_{AB}$ is the length of the arc of the circle measured on the inner hole; $L_{EF}$ is the length of the deformed arc between the points EF; $L_{CD}$ is the length of the deformed arc when the safety limit is reached between the CD points.
For the dimensional analysis of the circular hole, ten equidistant radial directions (blue lines in figure 18) were analyzed at 13 degrees between them. Thus we have analyzed four sectors of a circle in the central area which corresponds to the critical area, and every three sectors in the two lateral zones.

After several tests, a profile of the corrected hole which eliminate the thinning was obtained in (figure 19) which the radial directions for measuring the points and the initial hole having the color blue, respectively the corrected hole having the color green are indicated.

5.2 Determining of correction radius

The length of the arc of the circle between the 2 points A and B is calculated with the relation:

\[ L_{CD} = \frac{\pi \cdot R \cdot \alpha}{180} \]  

where: R is circle radius; \( \alpha \) - the arc angle in degrees.

In figure 20 is presented determination of radius which corrected the blank hole. Where R is initial hole and corrected radius is \( R_1 \) circle. In order not to reach the breaking limit, it is necessary to compensate with \( K = 29\% \) - the elongation limit of the material.

\[ \varepsilon = \frac{\pi R \alpha}{180} - \frac{\pi R_1 \alpha}{180} = \frac{R - R_1}{R_1} = k \]  

\[ R_1(1 + k) = R \]  

The radius of the new arc has the value:

\[ R_1 = \frac{R}{1.29} \]  

The \( R_1 = 77 \)-ray circle is used for correction, which is connected to the initial hole with radii of different values. Those results are presented in table 1.
Table 1. The obtained results.

| Test result | Hole geometry | Description |
|-------------|---------------|-------------|
| ![Image](image1.png) | ![Image](image2.png) | We use R30 to fillet |
| ![Image](image3.png) | ![Image](image4.png) | We use R50 to fillet |
| ![Image](image5.png) | ![Image](image6.png) | We use R80 to fillet |

5.3 Determining the profile equation

To determine the function that will generate the profile of the hole, we worked in Cartesian coordinates with the origin in the center of the hole and longitudinal plane of the die being the axis Ox. The number of the point at the intersection of the direction and whose coordinates are written in table 2 was noted.

![Figure 21](image7.png)

**Figure 21.** Determining the coordinates of the points on the corrected hole.
Table 2. Punched profile coordinates.

| No. crt. | xi     | yi     | Ѳi   |
|---------|--------|--------|------|
| 1       | 72.096 | 0      | 0    |
| 2       | 69.887 | 16.135 | 13   |
| 3       | 63.489 | 30.966 | 26   |
| 4       | 54.263 | 43.941 | 39   |
| 5       | 43.4   | 55.549 | 52   |
| 6       | 30.355 | 65.097 | 65   |
| 7       | 15.079 | 70.939 | 78   |
| 8       | 1.284  | 73.588 | 91   |
| 9       | -20.23 | 81.136 | 114  |
| 10      | -41.844| 82.123 | 127  |

Relationships are used to calculate the profile equation:

\[ Y = f(x) \]

\[ Y = b_0 + b_1 \cdot x + b_{11} \cdot x^2 \]  \hspace{1cm} (13)

\[ Y = b_0 + b_1 \cdot x + b_{11} \cdot x^2 \]  \hspace{1cm} (14)

where \( b_0, b_1, b_{11} \) are the coefficients to be determined.

To determine them, the following system of equations is used:

\[
B = (X^T \cdot X)^{-1} \cdot X^T \cdot Y
\]

\[
\begin{bmatrix}
 b_0 \\
 b_1 \\
 b_{11}
\end{bmatrix}
= \begin{bmatrix}
 y_1 \\
 y_2 \\
 y_3 \\
 y_4 \\
 y_5 \\
 y_6 \\
 y_7 \\
 y_8 \\
 y_9 \\
 y_{10}
\end{bmatrix}
\]

\[
X = \begin{bmatrix}
 1 & x_1 & x_1^2 \\
 1 & x_2 & x_2^2 \\
 1 & x_3 & x_3^2 \\
 1 & x_4 & x_4^2 \\
 1 & x_5 & x_5^2 \\
 1 & x_6 & x_6^2 \\
 1 & x_7 & x_7^2 \\
 1 & x_8 & x_8^2 \\
 1 & x_9 & x_9^2 \\
 1 & x_{10} & x_{10}^2
\end{bmatrix}
\]

After performing the calculations, the following coefficients were determined:

\[
b_0 = 73,89189; \\
b_1 = -0,28686; \\
b_{11} = -6,95388.
\]

The equation that determines the profile of the hole is:

\[ Y = f(x) \rightarrow Y = 73,892 - 0,287 \cdot x - 6,954 \cdot x^2 \]  \hspace{1cm} (17)

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6. Conclusions
Stress relief holes influence the deformation process and are important in terms of shape, size and position. Cracks that appear on the contour of the holes in the blank must be removed because they represent a risk of propagation on the part causing rejects. These cracks may be different from one batch to another due to the anisotropy of blank material. A balance must be made between the costs associated with the assimilation of such holes in the dies.

By this method of correction decreased the depth and width of the area of risk of propagation from edge of the hole.

There was a tendency for two areas to appear on the side of the corrected area depending on the connection radius between the correction radius and the initial radius. The risk of rupture is inversely proportional to the size of the connection radius.

A mathematical relationship must be determined to determine the connection radii in a future work. Also the results must be validated experimental.

7. References
[1] Hance B 2017 Practical Application of the Hole Expansion Test SAE Int. J. Engines 10
[2] Paul S K 2019 Effect of Punch Geometry on Hole Expansion Ratio Proc I. Mech. E. B 1-6
[3] Kim J H, Kwon Y J, Lee T, Lee K A, Kim H S and Lee C S 2018 Prediction of Hole Expansion Ratio for Various Steel Sheets Based on Uniaxial Tensile Properties Met. Mater. Int 1 24 pp187-194
[4] Yoon J I, Jung J, Lee H H, Kim G S and Kim H D 2016 Factors Governing Hole Expansion Ratio of Steel Sheets with Smooth Sheared Edge Met. Mater. Int 6 22 pp 1009-1014
[5] Paul S K 2019 The Efect of Deformation Gradient on Necking and Failure in Hole Expantion Test Manufacturing Letters 21 pp 50-55
[6] *** 2009 Hole expanding test ISO 16630:2009
[7] Yoshida H, Yoshida T, Sato K, Takahashi Y, Matsumo T and Nitta J 2013 Evaluation and Improving Methods of Stretch Flageability Nippon Steel Technical Report No. 103
[8] Păunoiu V, Nicoară D, Cantera Lopez A and Arroyo Higuera P 2005 Numerical simulation of forming limit curves using reduced scale samples The Annals of Dunarea de Jos University of Galati
[9] Hama T, Takamura M, Makinouchi A, Teodosiu Cristian and Takuda Hirohiko 2008 Effect of Tool-Modeling Accuracy on Square-Cup Deep-Drawing Simulation Materials Transactions 49 pp 278-283
[10] Banu M, Hama T, Alves L 2008 Numerical prediction of the stress fields in a bending-unbending stage using STAMP3D and DD3IMP Steel Research International 1 79 pp 186-193
[11] *** AUTOFORM Software manual