EQUIVALENT DRAWBEAD PERFORMANCE IN DEEP DRAWING SIMULATIONS

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ABSTRACT: Drawbeads are applied in the deep drawing process to improve the control of the material flow during the forming operation. In simulations of the deep drawing process these drawbeads can be replaced by an equivalent drawbead model. In this paper the usage of an equivalent drawbead model in the finite element code DiekA is described. The input for this equivalent drawbead model is served by experiments or by a 2D plane strain drawbead simulation. Simulations and experiments of the deep drawing of a rectangular product are performed to test the equivalent drawbead model performance. The overall conclusion reads that a real drawbead geometry can succesfully be replaced by the equivalent drawbead model.

1. INTRODUCTION

The manufacturability of deep drawn products strongly depends on the material flow into the die cavity during the deep drawing process. Usually this material flow is controlled by both the blankholder force and the contact conditions to secure part quality and to avoid wrinkling and tearing. However, applying a blankholder force is not an accurate tool to control the material flow, since the blankholder does not make contact with the entire blank due to thickness variations in the blank and tool deflections. Besides in some cases the required blankholder force may exceed the capacity of the press.

To improve the material flow control, drawbeads are used which are small protrusions appearing on the die surface. Because of these protrusions the material flow is restrained, causing a change of the strain distribution with consequently thinning of the blank (Wouters,1994), (Carleer,1994).

In the design trajectory of new products, deep drawing simulations are performed frequently, using a finite element program. The drawbeads should be modeled properly in a finite element code to guarantee an accurate simulation of its effects on the deep drawing process. However modeling the exact drawbead geometry requires a large number of elements due to the small radii of the drawbead. An equivalent drawbead approach is therefore commonly adopted in finite element codes to overcome this problem of CPU-time excess.

Most equivalent drawbead models represent the drawbead as an additional and constant drawbead restraining force (Kawka,1994), (Taylor,1993) disregarding the fact that this force depends on the stage in the process. The changes in the strain distribution and the thinning of the blank are not taken into account in these equivalent drawbead models, which results in inaccurate simulation results.

This paper presents an equivalent drawbead model which incorporates the restraining of the material flow and the effects of sheet thinning and strain changes. Both the drawbead restraining force (D.B.R.F.) and the plastic thickness strain are considered to be history dependent. In this model the real drawbead is replaced by an artificial line on the tool surface on which a numerical algorithm acts. The drawbead restraining forces and the plastic thickness strain which serve as input for the equivalent drawbead model can be obtained from experiments or from a 2D plane strain drawbead simulation, in which the real drawbead is accurately simulated.

The 2D drawbead model is discussed in the first part of this paper. The implementation of the D.B.R.F. and the plastic thickness strain in the equivalent drawbead model are briefly discussed in the second part of this paper. In the last part of the paper the correlation between the simulation results and the experimental results are presented.

2. 2D PLANE STRAIN DRAWBEAD MODEL

A 2D plane strain drawbead model is developed to obtain accurate data concerning the drawbead forces and thickness strain during the forming process. Once the reliability of this model is proven, it can be used to determine the drawbead forces and strains for all possible drawbead geometries.

The 2D model uses the Arbitrary Lagrangian Eulerian formulation, available in the finite element code DiekA (Huétink,1986), in which the material and grid displacement are uncoupled. The sheet is modeled with four layers of four node bi-linear plane strain elements. Contact between the sheet and the tools is described with contact elements (Huétink,1989). Figure 1 shows the 2D finite element mesh of a specific drawbead in which an extra bend is added to be able to directly compare the numerical results with the experimental data.

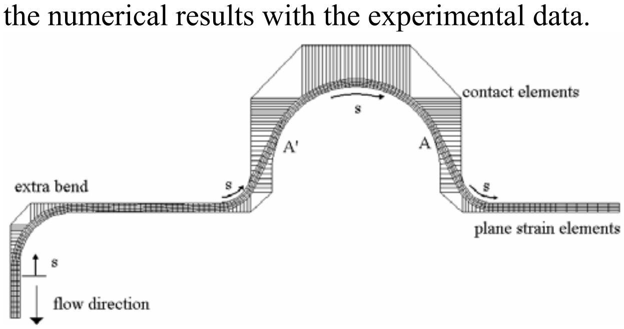

Figure 1. Finite element mesh of the 2D drawbead model

2.1 Experimental verification

An experimental set-up was built at Hoogovens Steelworks to validate the performance of the 2D plane strain drawbead model, see Figure 2.

In this part of the paper the numerical and experimental results will be compared for a specific drawbead geometry and a specific sheet material. The dimensions of the drawbead are listed in Table 1, the material properties are listed in Table 2.

The D.B.R.F. is recorded at the exit of the drawbead. The calculated D.B.R.F. needed to pull the sheet through the drawbead is shown in Figure 3 as a function of the material displacement. The D.B.R.F. appears to be history dependent with a steady state value of 106 N/mm.

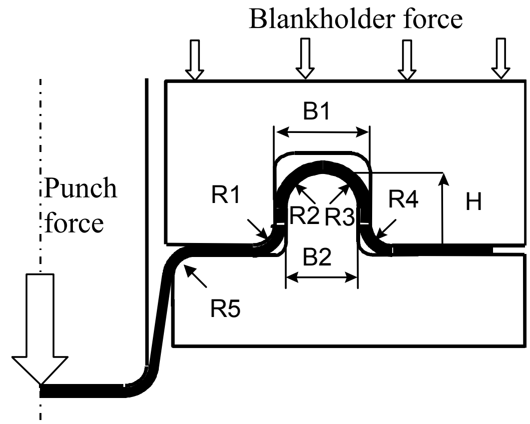

Figure 2. Drawbead test equipment

R1, R4	3 [mm]
R2, R3	8 [mm]
R5	5 [mm]
B1	20 [mm]
B2	16 [mm]
H	12 [mm]

Table 1. Geometry parameters of the drawbead

Ludwik value(C)	551 N/mm^2
hardening exponent (n)	0.230
initial yield stress	149 N/mm^2
sheet thickness	0.7 mm

Table 2. Material properties of the sheet

The measured D.B.R.F. is also shown in Figure 3. The stationary value of the measured force agrees very well with the calculated D.B.R.F. The large deviation between the experimental and numerical results for small displacement is due to a numerical effect. The finite element package DiekA makes use of a penalty method to describe contact behavior. At the beginning of the calculation the contact pressure in the contact elements is very small, yielding a significant penetration of the sheet in the drawbead tools. In the following displacement increments this penetration is reduced due to an increase of the contact pressure, which results in a higher D.B.R.F.

The plastic thickness strain in the sheet is calculated comparing the initial mesh with the deformed mesh and is depicted in Figure 4 as a function of the coordinate distance ‘s’ in the drawbead, see Figure 1. The plastic thickness strain is also history dependent, its steady state value reads –0.12.

The measured plastic thickness strain is also given in Figure 4 as a function of the co-ordinate distance in the drawbead. Again the experimentally determined plastic thickness strain agrees well with the simulations.

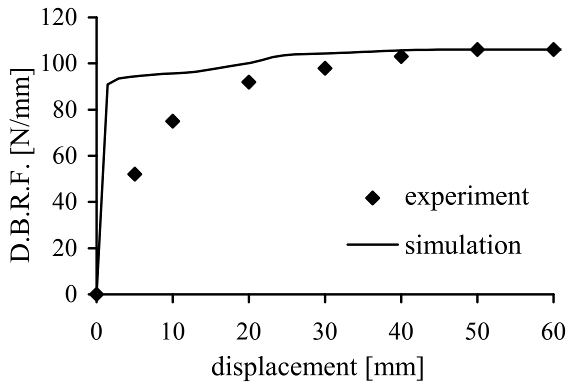

Figure 3. Drawbead restraining force

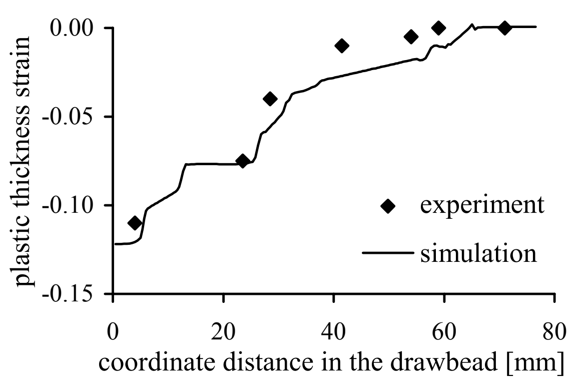

Figure 4. Plastic thickness strain

2.2. Analytical verification

The numerical 2D plane strain drawbead model can also be verified by a simple analytical model in which some simplifications are built in.
A moment M per millimeter width is needed to bend a strip with thickness t along a radius R, see Figure 5. Assuming a fully plastic moment and assuming that the neutral plane remains at its place, this momentum can be written as:

$$M = 2\int_0^{\frac{1}{2}t} \sigma_x y dy \qquad (1)$$

The material is assumed to obey both the Ludwik-Nadai hardening law and the Mises yield criterion. Hence, for the plane strain situation one can write:

$$\sigma_{ps} = \tfrac{2}{\sqrt{3}} C\varepsilon^n \quad \text{with} \quad \varepsilon = \frac{u}{x} = \frac{y\theta}{\left(R + \frac{1}{2}t\right)\theta} \qquad (2)$$

Substitution of equation (2) in (1) gives:

$$M = \frac{4C}{\sqrt{3}\left(R + \frac{1}{2}t\right)^n} \frac{1}{n+2} \left(\tfrac{1}{2}t\right)^{n+2} \qquad (3)$$

The force, needed to bend the strip can be calculated by equating the internal and external work.
The internal work yields:

$$W_{\text{int}} = \int\int \sigma\varepsilon dA = \int\int \sigma\kappa y dA = 2\kappa \int \int_0^{\frac{1}{2}t} \sigma y dy dx = \qquad (4)$$

$$= M\kappa\left(R + \tfrac{1}{2}t\right)\int_0^{\theta} d\alpha = M\theta$$

with curvature $\kappa = \dfrac{1}{R + \frac{1}{2}t}$ and strain $\varepsilon = \varepsilon_0 + \kappa y$.
The external work is given by:

$$W_{ext} = Fx \qquad (5)$$

The force per millimeter width can be calculated by equating equation (4) and (5):

$$F = \frac{M\theta}{x} = \frac{4C}{\sqrt{3}\left(R + \frac{1}{2}t\right)^{n+1}} \frac{1}{n+2} \left(\tfrac{1}{2}t\right)^{n+2} \qquad (6)$$

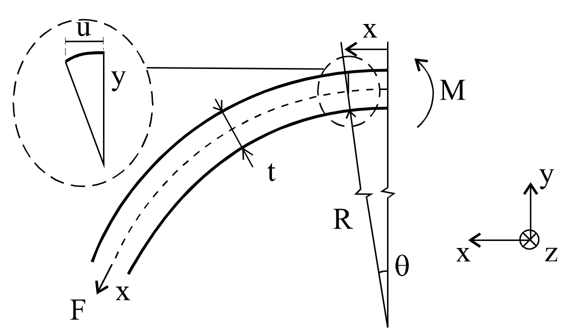

Figure 5. Principle outline for calculation of bending force

To compare the numerical result with this simple analytical model, a drawbead with dimensions given in Table 1 is chosen. The clearance is 0.7 mm which equals the blank thickness. The used material model will be ideal plastic with a C-value of 149 N/mm^2 and a hardening exponent of 0.0; friction is neglected.

Within this drawbead with a circular cross section the material will be bend and sequentially unbend two times around a radius of 3 mm and once around a radius of 8 mm. When the sheet thinning is neglected, the total Drawbead Restraining Force (D.B.R.F.) will be:

$$\text{D.B.R.F.}_{\text{analytical}} = 30.21 \text{ N/mm.}$$

The D.B.R.F. calculated with the 2D plane strain drawbead model amounts:

$$\text{D.B.R.F.}_{\text{simulation}} = 26.50 \text{ N/mm.}$$

One can conclude that the simulated D.B.R.F. compares well with the analytical solution, in where the analytical solution is an upperbound criterion due to the simplifications used.

3. EQUIVALENT DRAWBEAD MODEL

The equivalent drawbead model replaces the real drawbead geometry to avoid a drastic increase in CPU-time for deep drawing simulations. Furthermore the equivalent drawbead can be a flexible design tool; the effect of varying the position of the drawbead on the material flow can be studied very easily without the necessity to adapt the CAD-drawings for a variation in the position of the real drawbead. Another advantage of using an equivalent drawbead model is that it is more accurate in predicting the stress and strain state in the drawbead. This is due to the usage of volume elements in the 2D drawbead model. The deep drawing simulation, including drawbeads, is modeled with plate elements in which a plane stress state is assumed. When the drawbead radii are small compared to the sheet thickness, this plane stress situation does not hold. Replacing the real drawbead geometry by a numerical algorithm where the input is generated with the 2D drawbead model without this plane stress situation, a more accurate description of the deformation process is reached.

In this equivalent drawbead model the real drawbead is replaced by an artificial line on the tool surface, see Figure 6. A discrete material element passing this line will experience a history dependent D.B.R.F. and thickness strain.

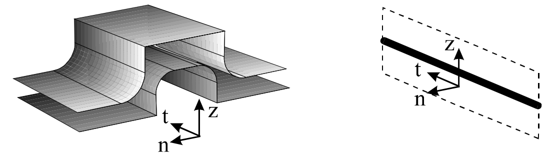

Figure 6. Schematic of a real drawbead and its equivalent representation

In the drawbead only the material flow in the normal direction ‘n’ causes the D.B.R.F. and plastic thickness strain whereas the tangential component ‘t’ does not contribute to those, see Figure 6 (Carleer,1996). This supports the approach to separate the total material flow in a normal and tangential component. Consequently, only the de normal component of the material flow is of interest for the equivalent drawbead model.

The implementation of the numerical algorithms to take into account the D.B.R.F. and the plastic thickness strain are not treated here. The reader is referred to (Meinders,1998).

4. APPLICATIONS

4.1 Strip drawing

First the performance of the equivalent drawbead model is verified by a strip drawing simulation. A simulation is performed in which the real drawbead geometry is modeled. In this simulation 1380 plate elements based on Mindlin theory are used. Second a simulation is performed in which the drawbead geometry is replaced by an equivalent drawbead model. For this simulation 600 plate elements based on Mindlin theory are used. The finite element models of both simulations are shown in figure 8. The plastic thickness strain of both simulations as a function of the co-ordinate distance are compared in figure 9. One can see that the maximum reduction in thickness of both simulations compare well. To make a fair comparison between both simulations it is necessary to draw the strip to a certain depth such that in both simulations the same amount of material has passed the drawbead and the shoulder of the die. Therefore the strip in which the equivalent drawbead is used has to be drawn deeper than in the simulation in which the real drawbead is of the

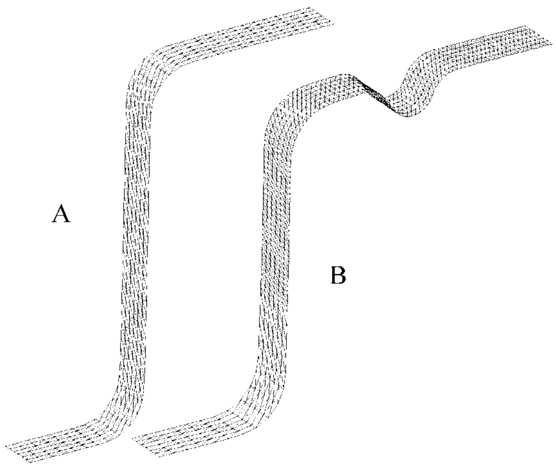

Figure 7 Finite element models of strip drawing with real drawbead (B) and with an equivalent drawbead (A)

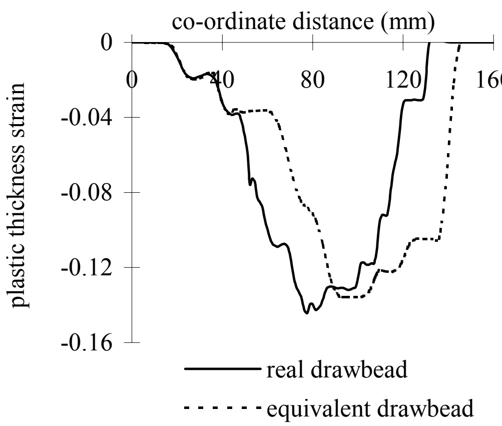

Figure 8. Plastic thickness strain

4.2 Deep drawing of a rectangular product

Next the equivalent drawbead model is applied in a deep drawing simulation of a rectangular product using the drawbead geometry given in Table 3. An experiment of this product is also performed for verification of the equivalent drawbead model.

Geometry	[mm]
R1, R3	3
R2	5
H	8
B1	13.6
B2	10
blank thickness	0.7
clearance	0.7

Table 3. Drawbead dimensions

The 2D plane strain drawbead model is used to determine the D.B.R.F. and the plastic thickness strain. The results obtained with the plane strain model are given in Figure 9 and will serve as input for the equivalent drawbead model.

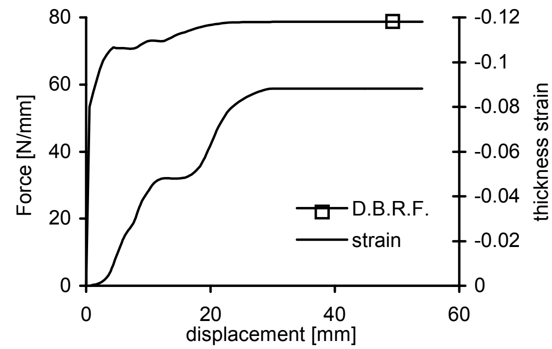

Figure 9. D.B.R.F. and plastic thickness strain distribution

The tool geometry for the rectangular product is given in . The dimensions of the tools and the blank are listed in Table 1. Drawbeads with a length of 200 mm are placed in the die-blank holder region, both at an distance of 126.8 mm in the positive and negative y-direction.

Tool description	***dimension [mm]***
punch length	400
punch width	200
radius punch shoulder	20
radius punch corner	20
die length	403.6
die width	203.6
radius die shoulder	10
radius die corner	20
product depth	100
Blank description	***dimension [mm]***
blank length	600
blank width	470
blank thickness	0.7

Table 1. Tool and blank dimensions

The blank is meshed with 4160 three node triangular plate elements based on Mindlin theory with 5 integration points over the thickness. Contact between the sheet and the tools is described with contact elements (Huétink,1989), in which a friction coefficient of 0.16 is assumed.

A rectangular product simulation, including the equivalent drawbead model with a prescribed D.B.R.F. and plastic thickness strain, is performed

using an elastic plastic material model. The results of the simulation after 100 mm deep drawing and the experiment are given in Figure 11.
It can be concluded that the calculated draw in compares very well with the experimentally determined draw in.

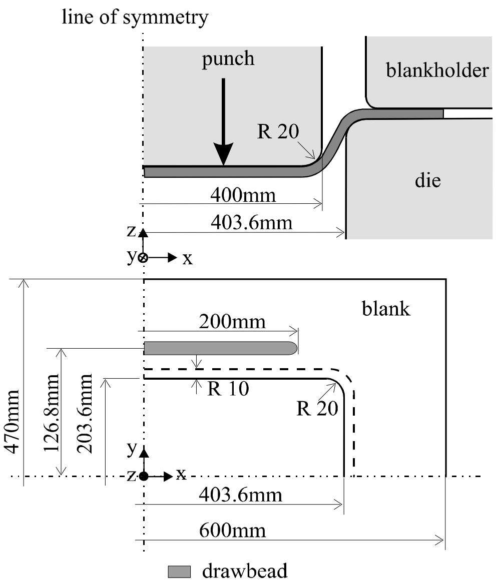

Figure 10. Tool geometry of the rectangular product

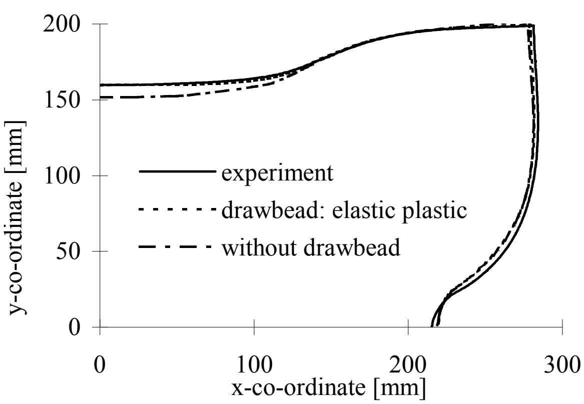

Figure 11. Flange shapes of the rectangular product

5. CONCLUDING REMARKS

- The 2D plane strain drawbead model gives an accurate prediction of the D.B.R.F. and the plastic thickness strain distribution.
- An equivalent drawbead model has been developed to avoid large computer time. The drawbead restraining force and plastic thickness strain, obtained by a 2D drawbead model or by experiments serve as input for this equivalent drawbead model.
- The equivalent drawbead restrains the material flow significantly. The simulation results compare very well with the experimental results and hence, the equivalent drawbead model is a powerful tool to replace the real drawbead geometry in deep drawing simulations.

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