DEEP DRAWING SIMULATION OF TAILORED BLANKS.

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SUMMARY:

Tailored blanks are increasingly used in the automotive industry. A tailored blank consists of different metal parts, which are joined by a welding process. These metal parts usually have different material properties. Hence, the main advantage of using a tailored blank is to provide the right material properties at specific parts of the blank.
The movement of the weld during forming is extremely important. Unwanted weld displacement can cause damage to both the product and the tool. This depends mainly on the original weld position and the process parameters. However experimental determination of the optimum weld position is quite expensive. Therefore a numerical tool has been developed for simulations of tailored blank forming. The Finite Element Code Dieka is used for the deep drawing simulations of some geometrically simple products. The results have been validated by comparing them with experimental data and show a satisfactory correlation.

1. INTRODUCTION

In conventional applications, car body panels are usually made of several smaller components. The components are formed individually and subsequently welded together to create the desired body panel. This approach entails high tooling, material and assembly costs. Moreover this process contributes to the dimensional inaccuracy in the assembly process. Therefore it can be attractive to form the body panels in a single stamping operation by using tailored blanks.
A tailored blank consists of several flat sheets that are welded together before forming. A combination of different materials, thickness, and coatings can be joined to form a blank for stamping car body panels. The main advantage of using a tailored blank is to have specific characteristics at particular parts of the blank, usually to reduce weight and costs. Particular parts of the blank can be made from a thicker or stronger material to increase the stiffness or strength locally while having thinner material for other parts. Moreover, alternative parts of the blank can be made of coated steel to increase the resistance to corrosion while having bare steel at other sections.

The use of tailored blanks offers several additional advantages with respect to product and process:

- improvement of tolerances, since the different parts of a product are welded together before forming using a continuous welding process
- reduction of the amount of scrap that arises because of the irregular shapes of the product. Smaller pieces of materials which form an irregular blank shape can be nested easily for better material utilisation
- reduction of the number of parts to be assembled, which results in simpler logistics
- reduction of (press-) handling including dies and installations
- improvement of crash durability: more controlled and larger energy absorption potential during collisions

Some of these advantages of tailored blanks can contribute to the development of lighter car design, resulting in a reduction of fuel consumption.

Tailored blanks are increasingly used in the production of automotive products. Some examples of car components made of tailored blanks are:

- A, B, and C pillars
- inner door panels
- longitudinals
- cross rail bumpers
- floor panels
- wheel houses
- inner panel tail gates

To apply high quality tailored blank products in the automotive industry, it is important to understand and predict the formability behaviour of tailored blanks during deep drawing. Therefore the influence of the weld location on the formability and the weld line motion must be investigated.

Shi [2] concluded that the amount of weld movement towards the stronger material is a measure for the strain localisation in the weaker base material. This weld movement strongly depends on the strength ratio and location of the base materials, and not on the weld type and weld width. Experiments performed by Saunders et. al. [1] indeed show the performance of a tailored blank to depend on the amount of weld movement. Prediction of the weld movement is therefore very important to predict the press formability (strain state, failure) of a tailored blank. The Finite Element Method may contribute to the prediction of tailored blank behaviour and its manufacturability.

2. SIMULATION SET-UP

To investigate the weld movement of tailored blanks during deep drawing, the finite element code DiekA [4] is used. A pre-processor for deep drawing of tailored blanks has been developed to generate input for the simulation program. The main characteristics of the strategy of this pre-processor and the way we used it are discussed in this section.

2.1 WELD MODELLING

There are two strategies to model tailored blanks in a finite element program. The first strategy is to model the weld accurately. In this situation the weld type is taken into account, i.e. the dimensions and the shape of the weld as well as the material properties in the weld and the heat affected zone. This approach requires a fine element mesh in the weld area and a thorough knowledge of the material properties of weld and heat affected zone. The second strategy is to neglect the weld type, only taking into account the place of the weld.

The second model strategy can be useful for deep drawing simulations without high local deformations in the weld area [3]. Since the appearing stress states in the products treated in this paper are expected to be relatively simple, the weld itself will not be modelled in the tailored blank simulations.

Two different weld types can be used in this model: laser welds and mash seam welds. Since laser welding appears to be used most widely, only laser welded tailored blanks are used in both experiments and simulations.

2.2 SHEET MODELLING

The blanks are modelled by three-node triangular plane stress elements. Three different element types are available to simulate the deep drawing of tailored blanks, i.e. membrane elements, which account for membrane stresses only, Kirchhoff elements, which account for bending stresses as well and Mindlin elements, which also account for shear stresses. Considering the geometry of the simulated products, the bending stresses and the shear stresses are expected to be of less influence then the membrane stresses. Therefore in general it will be sufficient to use membrane elements. In some specific cases, in order to check the validity of this assumption, we used Mindlin elements.

For contact description between the sheet and the tool special 6-node triangular contact elements are used [5]. With these contact elements, the contact behaviour as well as the friction behaviour during the deep drawing process can be described.

As mentioned before, the weld itself will not be modelled but will be represented as a simple boundary condition between different base materials. The schematic geometry of a tailored blank (figure 1) shows a flat side (top) and a non-flat side (bottom).

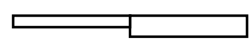

Figure 1. Schematic geometry of the Tailored Blank

The material behaviour can be described with a Hill rigid plastic material model or elastoplastic material model and either isotropic or anisotropic material. The elastoplastic material model is more accurate than the rigid plastic model, however it is numerically less stable and more time consuming than the rigid plastic model. Most simulations were performed using isotropic rigid plastic material behaviour. In some cases the anisotropic elastoplastic model was used (see 4.1), yielding a better description of the behaviour of the flange and earing.

2.3 TOOL MODELLING

Since deep drawing of tailored blanks differs from deep drawing of uniform blanks, the tools have to be adapted, notably when base materials with a different thickness are joined. The necessary adaptations are summarised below for each deep drawing tool, assuming different thickness of the base materials.

Blankholder

A flat rigid blankholder cannot be used for tailored blank forming with different thicknesses, since wrinkling in the thinner base material during deep drawing cannot be prevented and the blank holder force cannot be varied over the product flange. Possible adaptations to the blank holder to avoid these wrinkles are a stepped rigid blankholder, a deformable blankholder and a segmented blankholder which allows individual force control per segment.

For this paper some experiments were performed with a stepped rigid blankholder and some experiments were performed using a segmented blank holder The latter prevents both wrinkling and premature tearing due to a variable blankholder force over the product flange (see 3.1).

Commonly the weld line in the bottom of a product moves towards the thicker base material, resulting in a higher material flow out of the flange into the die cavity for the thinner base material. This yields a weld line motion towards the thinner base material in the product flange. To avoid damage of the blankholder during deep drawing caused by the thicker base material a tool offset between the thicker blank and tool step can be created in the blankholder.

Punch

The punch also can be adapted to the difference in thickness. The differences in thickness however were rather small, so both the relatively expensive adaptation of the real punch and the modelling were deemed not necessary.

Die

If the non-flat side of the tailored blank is turned towards the die, the die has to be adapted. In this case we used laser-welded blanks with the non-flat side turned towards the punch and blankholder, so adaptation of the die was not necessary.

3. EXPERIMENTAL SET-UP

The blanks were welded at Automotive Tailored Blanks, parallel to the rolling direction. The experiments have been performed at the Research & Development department of Koninklijke Hoogovens NV.

3.1 TOOLS

The products have been deep drawn on a 300 tons SMG-press. Only laser welded tailored blanks have been produced and pressed. Three types of punch geometry were used: cylindrical, hemispherical and square (table 1). Round blanks were used for round products. Octagonal blanks and square blanks with a centred hole were used for square products. To overcome the problem of thickness deviation with respect to the blankholder the blankholder was adapted. In case of the axisymmetrical punch rings with a step in thickness have been placed between the blankholder and the thinner base material, so creating a stepped rigid blankholder. The tools for drawing square products have been developed at and bought from DAF Trucks, located in Eindhoven, and include a segmented blankholder, permitting an independent blankholder pressure and force on each constituent part of the tailored blank.

Geometry punch	cylinder	hemisphere	square
punch diameter (mm)	293	293	-
width (mm)	-	-	360
punch shoulder (mm)	20	20	20
die shoulder (mm)	20	20	10
punch/die corner (mm)	-	-	80

Table 1. Tool geometry

3.2 BLANKS AND PRODUCTS

The round tailored blanks have been lubricated with machine oil Lical EP2, the octagonal and square ones with different lubricants as well as plastic film. Unfortunately the precise quantity and the properties of the lubricant were unknown, so an exact value for the friction coefficient could not be used. It is estimated to lie between 0.12 and 0.15.

Four base materials have been used to create three different thickness combinations for the tailored blanks. The material properties of these materials (all uncoated FeP04) are listed in table 2.

Steel	I	II	III	IV
thickness (mm)	0.7	0.8	1.0	1.5
C	544	521	549	543
Rp (MPa)	168	171	173	169
n	0.221	0.217	0.234	0.223
R_0	1.842	1.866	1.971	1.710

Table 2. Material properties

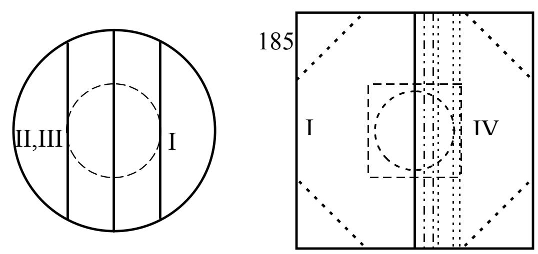

Figure 2. Blank geometry with possible weld positions (see below), punch (square) & hole(round) shown as dashed lines

The blank geometry and possible weld lines are shown in figure 2. The original weld line positions of the octogonal blank were: at x=0 (centre), x=100, x=140 and x=180 mm. For the square blank the positions were: x=0 (centre), x=40 and x=80 mm. Note that each blank contains only one weld. In case of the round blanks three weld line positions combined with two thickness combinations and two punch geometries yield twelve products. With the octagonal blanks four weld line positions were possible, resulting in eight different products. The square blanks with a hole were made with three different weld positions, thus producing six different products. The relevant blank parameters are listed in table 3.

Geometry blank	round	octagonal	square
blank diameter (mm)	480	-	-
width (mm)		650/280	650
hole diameter (mm)	-	-	160
weld at ..mm from centre	-130, 0, 130	0, 100, 140, 180	0, 40, 80
material combinations	II+I, III+I	I+I, I+IV	I+I, I+IV

Table 3. Blank parameters

4. RESULTS OF DEEP DRAWING TESTS AND CALCULATIONS

Several products have been made for each geometrical situation: 6 cylindrical, 6 hemispherical, 8 square without hole and 6 square with hole. Because of the symmetry only half of the blanks and tools had to be modelled. The average calculation time took 8 to 12 hours on a HP 700-series workstation. Inaccuracy of the calculated unbalance was usually below 1%. Meshes contained up to 13000 nodes and 5000 membrane elements.
In general the simulation results agreed quite well with the experimental results. The movement of the weld was the main criterion for comparison.
The deep drawing experiments for the round product succeeded with only a small number of failures, but some adaptations to the process had to be made: in order to prevent tearing the blankholder force had to be different on the thick and the thin part. The numerical model was partly corrected for this by also applying different forces to both parts. However, since for the round products a stepped rigid blankholder was used, the force distribution over the blankholder was not known exactly and could not be properly modelled. Therefore the blankholder was finally modelled as a segmented blankholder.
The blankholder pressure on the thicker part of the octagonal blank in the square tools was 1.0 N/mm^2, on the thinner part 1.8 N/mm^2. The square blanks with a hole were drawn using a lockbead, thus minimising material flow inwards. In the numerical model this was simulated by using an very high blankholder force. Another means to reduce failure was the amount and type of lubricant used.
In the next paragraphs more details are given and some examples are shown.

4.1 CYLINDRICAL CUPS

Table 4 shows the weld displacements in x-direction (perpendicular to the weld) for all simulations at the centre and at the edge of the flange. Minimum and maximum values for the real products, including an estimated error of -2.5/+1.5 mm, are presented. The experimental values were taken from cups drawn partly with different measured blankholder forces and amount of lubrication, but the difference was in the order of the inaccuracy in the modelling of the blankholder force. Bold printing indicates a calculated value not within the experimental range. The general impression concerns both actual position and general shape of the weld lines.
As expected the weld line tends to shift towards the thick part at the centre, and towards the thin part in the flange. This depends of course on the blankholder force used. For 2 of the 6 cases the calculated weld line fits very well between the minimum and maximum of all measured lines. In one case the shape of the curve also fits extremely well.

Cylindr.	1.0-0.7 mm			0.8-0.7 mm		
Weld pos.	-130	0	130	-130	0	130
At centre:						
meas. min	-18.13	-1.18	-6.96	-18.18	-2.72	-3.77
meas. max	-8.67	5.40	6.81	-4.97	3.43	2.85
calc.	-8.72	1.58	**12.90**	-16.00	1.56	**4.72**
At flange:						
meas. min	-9.25	-0.98	-36.62	-9.71	-0.01	-37.82
meas. max	3.60	4.45	14.60	9.42	4.92	-30.52
calc.	**8.04**	1.65	-19.20	4.27	1.51	**-23.00**
General fit	good	good	good	good	good	good

Table 4. Cylindrical punch: shift of weld line, measured and calculated at centre and flange (mm); general impression of comparison between measured and calculated weld line.

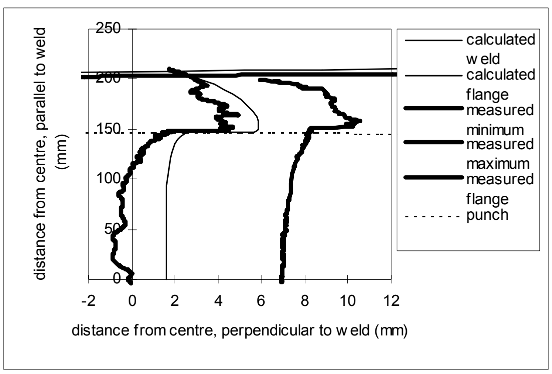

Figure 3. Calculated and measured weld line for a cylindrical cup, original weld position at centre and thickness 1.0 mm (left) and 0.7 mm (right)

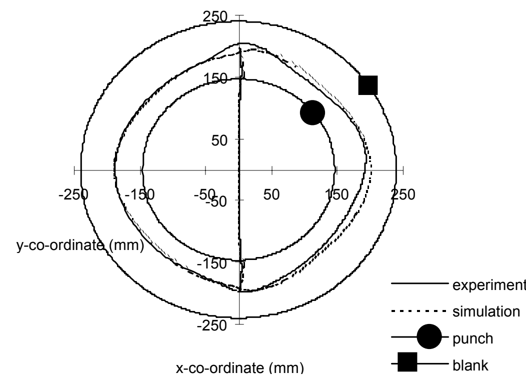

Figure 4. Flange and weld line using an anisotropic elastoplastic model

The other 4 lines could be moved linearly within the error boundaries of the measurements to coincide with the measured line. As an example figure 3 shows the weld displacement in a cylindrical cup of 100 mm height, drawn from a tailored blank consisting of 1.0 mm (left) and 0.7 mm (right) steel. The blankholder force was appr. 130 kN on the thick part and 200 kN on the thin part in order to prevent wrinkling and tearing. The smooth lines represent calculated data, the irregular fat lines measured data. The agreement is quite good.
In this particular case the calculation was repeated using Mindlin elements and an elastoplastic material model, also accounting for anisotropy (fig. 4). This produced a better flange than the original isotropic/rigid plastic model. The weld displacement however does not seem to be very different. The other simulated situations show comparable results regarding the weld position and flange shape.

The last criterion for comparison was the punch force curve. The measured punch force was compared with the calculated punch force. Unfortunately these curves did not fit very well. An explanation for this discrepancy may be found in the inaccurate way the blankholder force was modelled in case of different values left and right. Actually the agreement was far better in the few cases we could use a uniform blankholder force.

4.2 SPHERICAL CUPS

In general the calculations on forming spherical cups show less satisfactory results. Both weld and flange compare less well to the measured curves. To illustrate this the measured and calculated weld and flange of the spherical cup consisting of a smaller part of 0.7 mm and a larger part of 0.8 mm are shown in figures 5 and 6. In figure 5 the weld line displacement can

Hemisph..	1.0-0.7 mm			0.8-0.7 mm		
Weld pos.	-130	0	130	-130	0	130
At centre:						
meas. min	-8.72	-9.40	-12.77	-7.10	-8.75	-9.13
meas. max	4.24	-1.87	-1.65	-1.22	-0.59	-7.50
calc.	3.27	-8.02	-11.80	3.07	**0.95**	**-11.10**
At flange:						
meas. min	-5.88	-0.60	-22.46	-4.86	-6.57	-25.28
meas. max	1.66	5.10	-15.63	0.27	1.59	-21.56
calc.	**6.72**	3.65	**2.97**	-2.09	1.37	**6.00**
General fit	fair	good	good	good	poor	fair

Table 5. Hemispherical punch: shift of weld line, measured and calculated at centre and flange (mm); general impression of comparison between measured and calculated weld line.

be seen. Although the shape of the calculated curve at the centre (near y=0) is more or less similar to the measured curve, the calculated weld line at the flange does not shift as far to the left as the measured weld. Looking at figure 6 the differences in flange shape are even larger. The measured flange circumference shows considerable earing, which, naturally, can not be predicted with calculations assuming an isotropic material. Using a rigid plastic material model also did not improve the results. Furthermore the inaccurate approach of the blankholder force is a cause of the difference: in this case the blankholder force on the thin

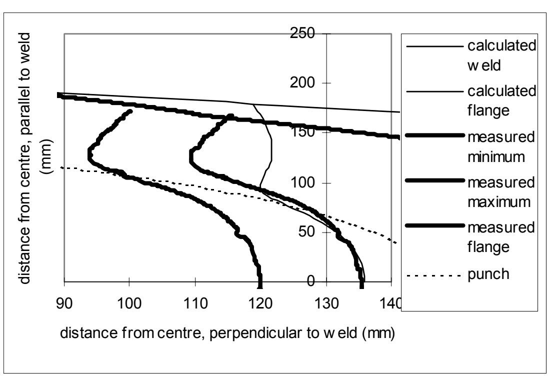

Figure 5. Calculated and measured weld line for a spherical cup, original weld position at 130 mm and thickness 0.8 mm (left) and 0.7 mm (right)

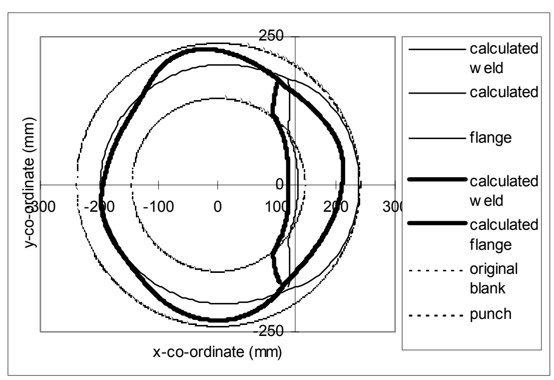

Figure 6. Calculated and measured flange and weld

part was twice as heigh as the force on the thick part.
This weld position in combination with the hemispherical punch geometry induces a strain that is neither perpendicular nor parallel to the weld. In such a case the weld probably should also be modelled.

Finally the measured flange is seen to be asymmetrical in the vertical direction, which can not be simulated when considering only the upper half of the geometry.

4.3 SQUARE PRODUCTS WITHOUT HOLE

Sq./oct.	0.7-1.5 mm				0.7-0.7 mm			
Weld pos.	0	100	140	180	0	100	140	180
At centre:								
measured	10.90	15.40	13.30	-0.50	0.20	1.60	0.30	-1.80
calculated	6.54	*est. 14*	8.57	-2.02	0.02	*est. -1.1*	-	-5.55
At flange:								
measured	-18.05	-9.00	-21.65	-11.90	-2.10	-9.85	-24.15	-15.25
calculated	-10.83	*est. -22*	-25.97	-27.99	-0.10	*est. -17*	-	-18.98
General fit	good	*good*	good	poor	good	*fair*	-	fair

Table 6. Square punch/oct. blank: shift of weld line, measured and calculated at centre and flange (mm); general impression of comparison between measured and calculated weld line.

In this case unfortunately there was a misunderstanding about the exact position of the weld before drawing. Due to this only five calculations matched the conditions of the press trials

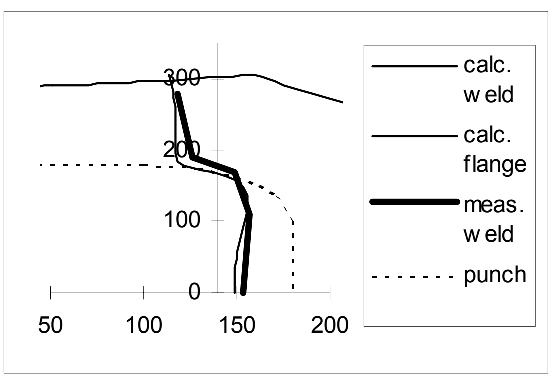

Figure 7. Calculated and measured weld for 1.5-0.7 mm thickness combination, y-axis indicates original weld position at 140 mm.

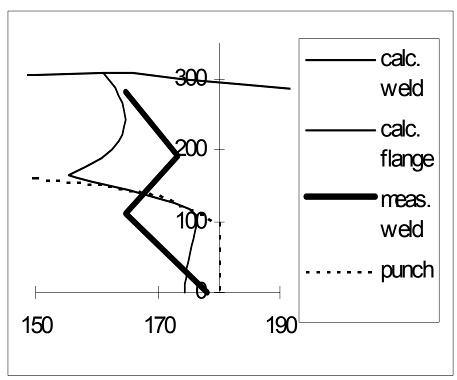

Figure 8. Calculated and measured weld, 0.7-0.7 mm thickness combination, , y-axis indicates original weld position at 180 mm.

well enough. Two calculations were performed with a weld that was slightly out of position, so we could estimate what the weld in the formed part should be. Only one calculation could not be performed in time for this paper. Altogether 6 out of 7 calculations showed a reasonable or good result. The error in these measurements is unknown, but is supposedly about 5 mm to both sides. Furthermore the y-position is not known exactly.

The calculated weld line motion agrees quite well for both thickness combinations with the experimental data. Unfortunately the accuracy of these measurements is quite poor: only the x-positions of 3 to 5 points on the weld line were measured. On the other hand the modelling of the blankholder force is more accurate, because the blankholder consists of two separate and independent parts and the force on each part of the blank therefore is well defined and known. In most cases the calculated weld lines fit reasonably well, with the exemption of the 0.7-1.5 combination with an original weld line position at 180 mm (right on the shoulder of the punch). Here the strain, like in the example in 4.2, is also non-perpendicular and non-parallel in places. One example (fig. 7) shows the displacement of the weld that was originally situated at 140 mm: the agreement is quite well. One other example (fig. 8) is the product having the 0.7-0.7 mm combination with the weld originally at 180 mm. Although the calculated weld position at minimum and maximum does not agree with the measured value, on the bottom and at the flange the agreement is better and the shape in general is also quite similar to the measured weld.

4.4 SQUARE PRODUCTS WITH HOLE

The first three types of experiments were more or less academical: in the press shop symmetrical square and round cups are seldom found. Therefore experiments and calculations were performed on stretching blanks with a hole, thus simulating the "real life" situation of drawing a part with a weld bordering a hole, like a window.
In this situation the blankholder is closed tight using lockbeads to prevent draw in of the blank. The blank has a hole in the middle and the material flow is clearly from this hole outwards. The height of the products ranges from 17.5 mm up to 42.7 mm (table 8).
Figure 9 shows an example of the positions of measurements. The shift in x-direction of the weld was taken at the intersection of the weld with the hole and on the point where the flange started, just adjacent to the die shoulder. Again the thickness combinations 1.5-0.7 mm and 0.7-0.7 mm have been used. The initial weld line positions were 0, 40 and 80 mm from the

Sq./hole	0.7-1.5 mm		0.7-0.7 mm		
Weld pos.	0	80	0	40	80
At rim hole:					
measured	4.05	16.40	0.70	14.25	6.90
calculated	2.46	7.79	0.80	10.18	0.14
At rim die:					
measured	1.40	2.25	0.50	0.20	0.50
calculated	0.78	1.67	0.92	0.30	0.32
Hole diam.x					
measured	172.9	191.4	221.3	214.2	175.0
calculated	179.4	181.0	170.8	198.4	172.6
General fit	fair	fair	good	good	poor

Table 7. Square punch/blank with hole: displacement of weld line, measured and calculated at centre and flange (mm); x-diameter hole; general impression of comparison between measured and calculated weld line.

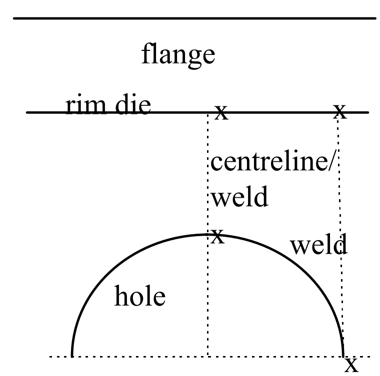

Figure 9. Measurement points

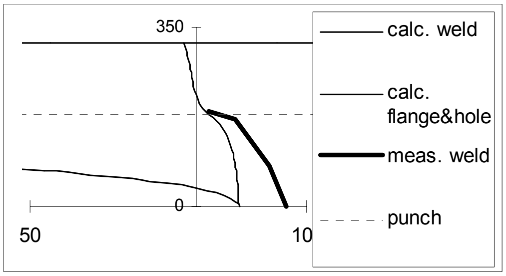

Figure 10. Calculated and measured weld for 1.5-0.7 thickness combination, y-axis indicates original weld position

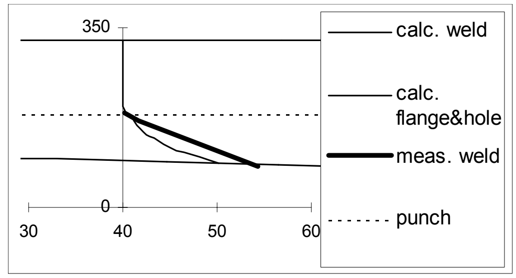

Figure 11. Calculated and measured weld for 0.7-0.7 thickness combination, y-axis indicates original weld position

centre. In two cases out of these five the calculations predicted the actual weld line quite well. In the symmetrical situation (0.7-0.7, weld at 0) the difference between measured and calculated weld was less than the element length. The measured weld line in this case, like the calculated line, hardly shifted (< 1 mm to the right). One calculation could not be performed. Due to an uptil now unknown cause the calculations on the blank of 0.7-1.5 mm thickness with the weld at 40 mm from the centre could not be run.

Thick.	**Weld**	**Height**
1.5-0.7	0	17.5
1.5-0.7	80	27.3
0.7-0.7	40	39.5
0.7-0.7	80	19.0

Table 8. Drawing height for each weld position and thickness combination, all mm

Figures 10 and 11 give an impression of the results of the calculations on the 1.5-0.7 mm combination with the weld in the undeformed blank tangent to the hole at 80 mm from the centre and the 0.7-0.7 mm combination having the weld in the undeformed blank at 40 mm from the centre. Apparently the measured weld moves farther out. In most cases the hole itself is also larger. Together with the calculated weld displacement (fig. 10) this leads to the conclusion that either the modelled blankholder force was insufficient to simulate the use of lockbeads or lubrication.

5. CONCLUSIONS.

The simulation results correlate quite well with the experimental results for the round product, especially with respect to the weld line motion.
In case of the square products, the actual circumstances during the press trials were not known exactly. Therefore the simulation results of this part of the study do not always correlate well with the experimental data.
The weld line motion is significantly influenced by the occurring strain state, especially when the material is stretched perpendicular to the weld, due to strain localisation in the thinner (weaker) base material. A minimisation of weld displacement can be achieved by placing the weld in a region with low strains perpendicular to the weld line or to choose the load bearing capacities of the applied base materials equal.
The elastic plastic material behaviour is preferred to the rigid plastic material behaviour, since in the elastic plastic model the strains are not overestimated in low strained areas.

Probably the weld itself has to be modelled when the weld is subjected to strain states which are not predominantly perpendicular to the weld line. Further investigation must be done to verify this.
The Finite Element Method can be used to predict the stress state, strain state and weld line motion during deep drawing, under the assumption that the blankholder force is decribed accurately.

6. ACKNOWLEDGEMENTS

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F. Aben is thanked for making his results available with respect to the square products.

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