Influence of asymmetrical drawing radius deviation in micro deep drawing

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Abstract. Nowadays, an increasing demand for small metal parts in electronic and automotive industries can be observed. Deep drawing is a well-suited technology for the production of such parts due to its excellent qualities for mass production. However, the downscaling of the forming process leads to new challenges in tooling and process design, such as high relative deviation of tool geometry or blank displacement compared to the macro scale. FEM simulation has been a widely-used tool to investigate the influence of symmetrical process deviations as for instance a global variance of the drawing radius. This study shows a different approach that allows to determine the impact of asymmetrical process deviations on micro deep drawing. In this particular case the impact of an asymmetrical drawing radius deviation and blank displacement on cup geometry deviation was investigated for different drawing ratios by experiments and FEM simulation. It was found that both variations result in an increasing cup height deviation. Nevertheless, with increasing drawing ratio a constant drawing radius deviation has an increasing impact, while blank displacement results in a decreasing offset of the cups geometry. This is explained by different mechanisms that result in an uneven cup geometry. While blank displacement leads to material surplus on one side of the cup, an unsymmetrical radius deviation on the other hand generates uneven stretching of the cups wall. This is intensified for higher drawing ratios. It can be concluded that the effect of uneven radius geometry proves to be of major importance for the production of accurately shaped micro cups and cannot be compensated by intentional blank displacement.

1. Introduction
Due to the growing influence of technical devices such as smartphones and tablet computers in our daily life an increasing demand for micro components can be observed as predicted by [1]. As defined by [2] electronic items consist of a great number of metallic micro components like housing parts with dimensions smaller than 1 mm. Considering the high number of electronic devices sold worldwide like for example roughly 45 million iPhones in the last quarter of 2016 [3], cost and energy efficient production has to be ensured. Considering these demands, forming processes such as deep drawing seem like an ideal choice due to their high efficient use of material and fast rate of production [4]. However, downscaling of conventional drawing processes to the micro range leads to new challenges. Size effects cause changes in formability [5] and tribology [6] leading to smaller process windows [7]. Additionally,
decreased tool size leads to higher relative geometry deviation because accuracy of conventional manufacturing is limited [8]. A deeper understanding of the influence of tool geometry on process stability in micro deep drawing is needed. In former investigations, symmetrical process deviation have been studied. A change of die clearance resulted in greatest impact on the punch force and limiting drawing ratio. Instead, a change of the die radius had a strong influence on limiting drawing ratio but caused only a small change in punch force [9]. Former investigations focused on symmetrical deviations. This study shows a more realistic approach that makes it possible to determine the impact of asymmetrical process deviations and position accuracy in micro deep drawing.

2. Method of investigation
The goal of the investigation is to identify the influence of asymmetric radius deviation on the shape accuracy of micro deep drawn cups because during manufacturing of micro drawing dies geometry deviations occur. Drawing radius or tool geometry curvature is crucial for forming processes, therefore they are predefined. For circular geometries curvature $c_z$ is defined as the inverse radius $r_z$. The influence of drawing radius and curvature is investigated by the use of a drawing die with varying radius deviation dependent on the angular position $\omega$ as shown in figure 1.

![Figure 1. Schematic view of die geometry.](image)

At an angular position of $\omega = 0^\circ$, which is defined as positive x-direction, the biggest radius $r_z,max$ and at an angular position of $\omega = 180^\circ$, which is defined as negative x-direction, the smallest radius $r_z,min$ is used. For the description of the resulting geometry the ratio of maximum curvature $c_z,max$ relative to the minimum $c_z,min$ is introduced and defined as:

$$ROC = \frac{c_z,max}{c_z,min}$$

(1)

Four different radius geometries with increasing difference between maximum and minimum radius and a constant average radius $r_z,0 = 77 \mu m$ are investigated in a parametric study with the use of FEM-analysis. The results are verified by results from deep drawing experiments. In figure 2 the drawing radius is plotted over tangential angular position on the drawing die. The four tool geometries used in FEM-Analysis are represented by circles and the tool used in experiment is represented by triangles. In all cases the smallest radius can be found at a position of $\omega = 180^\circ$ and the biggest radius is located at a position of $\omega = 0^\circ$. In order to determine the drawing radius geometry used in experiment, a laser scanning microscope Keyence VK 9700 was used. The drawing die was positioned at a 45° angle under the microscope as shown in figure 3 (a). A horizontal position leads to increased scattering at the inner part of the drawing radius. In this way, the complete radius geometry can be detected. The radius was analyzed by fitting a 3-point circle to the detected geometry. This was performed eight times distributed evenly along tangential angular position $\omega$. 

[Image 156x373 to 439x519]
As a quantitative measure for shape accuracy of the deep drawn cup the height difference $\Delta h$ between highest side $h_2$ and lowest side $h_1$ of the cups wall is introduced and defined in equation (2). This is detected using a Keyence VHX 1000 digital microscope as shown in figure 3 (b). After identifying the lowest and highest side the average cup height have is computed using equation (3).

$$\Delta h = h_2 - h_1$$  \hspace{1cm} (2)

$$h_{ave} = \frac{h_1 + h_2}{2}$$  \hspace{1cm} (3)

### 3. FEM-analysis

For FEM-analysis, the software Abaqus 6.14 was used. A 3-dimensional model for micro deep drawing was used. All tools are defined as analytical rigid shell objects and the blank was defined as a deformable body using the 8-node linear brick 3D-stress element C3D8R for the mesh. Within the sheet thickness four elements were used. In order to save computational time only one half of the blank was considered. For the elastic plastic material model of the stainless austenitic nickel-chromium steel 1.4301 (X5CrNi18-10) with a thickness of 25 $\mu$m tensile tests were performed to determine the required flow...
stress curves as described in [10]. A constant friction coefficient of $\mu = 0.23$ was identified numerically by comparing punch forces in experiment and simulation as proposed in [11]. For analysis of curvature deviation four different radius geometries were prepared using the software Autodesk Inventor 2017 and then imported in the pre-processor of Abaqus. The radius geometries were designed by specifying three different radius $r_{\min}, r_0$ and $r_{\max}$ spread evenly on the tool over 180°. The surface in between those three points was interpolated. While $r_0$ was kept constant for all geometries $r_{\min}$ was decreased and $r_{\max}$ was increased leading to four different geometries as shown in figure 2.

4. Experimental setup
For deep drawing experiments described in this investigation circular blanks made of stainless austenitic nickel-chromium steel 1.4301 (X5CrNi18-10) were used. The material was rolled to a thickness of $s_0 = 25 \, \mu m$ and annealed by the manufacturer to assure minimal anisotropy. The blanks were cut out using a picosecond pulsed laser with a wave length of 1030 nm in order to prevent burr formation at the edge of the blank. To investigate the influence of process deviation for different drawing ratios, three different initial blank diameters $D_0 = 1.7 \, mm, 1.8 \, mm$ and $1.9 \, mm$ were cut out. The diameters were checked with a Keyence VHX 1000 digital microscope. For the tools ledeburitic powder-metallurgical steel 1.2379 (X153CrMoV12) was used. The relevant geometric parameters of the tools used in experiment were measured using laser scanning microscope Keyence VK 9700 and are summarized in table 1. The drawing process was carried out on a single axis micro forming press with a maximum punch force of 500 N and a constant punch velocity of 10 mm/s using HBO 947/11 as lubricant. The punch force was measured with a Kistler 9217A piezo load cell with an accuracy of 0.01 N. Punch displacement was measured with a Heidenhain LS477 linear scale with an accuracy of 1 $\mu m$. The press is driven by a servo motor controlled by a NI 9514 servo drive interface. The blank holder acts passively. It uses its own weight and is supported by two springs. Blank holder pressure can be adjusted by changing the spring tension and was set to $P_{\text{NHD}} = 5 \, MPa$. The blank positioning was realized by an automated positioning system. The blank was positioned with a pneumatic gripper that is driven by a linear direct drive cross table. The position of the blank was then measured using an Allied Vision G 917 B monochrome CCD camera with a resolution of 9 MP equipped with a telecentric lens with built-in coaxial illumination and a magnification of 0.75. With this setup the blanks can be positioned within a radius of 10 $\mu m$ from the centre of the drawing die.

Table 1. Specifications of tool geometry used in experiment.

| Specifications                      | 1.005 | 0.110 | 1.061 | 0.077 | 1.120 | 2.923 |
|-------------------------------------|-------|-------|-------|-------|-------|-------|
| Punch diameter (mm)                 |       |       |       |       |       |       |
| Punch radius (mm)                   |       |       |       |       |       |       |
| Drawing die diameter (mm)           |       |       |       |       |       |       |
| Average drawing die radius (mm)     |       |       |       |       |       |       |
| Drawing gap (factor x foil thickness) (mm) |       |       |       |       |       |       |
| Ratio of curvature ($c_{max} / c_{min}$) |       |       |       |       |       |       |

5. Results
In figure 4 the absolute cups height difference determined in FEM analysis and experiment is shown. Each experimental value stands for ten deep drawn cups. The height difference is plotted over the blank position. Positive x-direction stands for a movement towards the side of the tool with minimum curvature $c_{z,\min}$ and negative x-direction means a movement towards the side with maximum curvature $c_{z,\max}$. If the blank is positioned with a negative offset the height difference increases linearly while a displacement in the opposite direction leads to a linear reduction of cup height difference. Independent from the curvature profile the same gradient of change in absolute height difference can be observed for all investigated radius geometries in FEM-analysis.
Figure 5 shows the cup height difference in FEM-analysis without blank displacement for different ROC. A ROC = 1 represents the ideal tool and leads to an ideal cup shape with equal wall height. If ROC is increased the absolute height difference increases linearly. The maximum investigated ROC = 2.9 results in a height difference of $\Delta h = 110 \, \mu m$ which equals 17% of the average cup height.

Figure 4. Influence of blank displacement and ROC on height difference of deep drawn cups.

Figure 5. Height difference of deep drawn cups in FEM-analysis.

In figure 6 the cup height difference relative to the average cup height is shown for different drawing ratios. If the drawing ratio is raised from $\beta = 1.7$ to $\beta = 1.9$ the cup height difference in experiment is increased from 12% to 17% of the average cup height $h_{ave}$ (black triangle). At the same time the standard deviation decreases from 9% to 6% of the average cup height for blanks positioned within a distance of 10 $\mu m$ from the center of the drawing die. In FEM-analysis with equal ROC and centric positioned blanks (blue circle) the same tendency for relative cup height difference can be observed. A
displacement of ± 10 µm results in a change of height difference of ± 12 % for a drawing ratio of β = 1.7 and reduces to ± 7 % of the average cup height for a drawing ratio of β = 1.9. For a ROC = 2.9 a calibration of cup height difference can be achieved for a drawing ratio of β = 1.7 and a blank displacement of - 15 µm.

Figure 6. Influence of curvature deviation and drawing ratio on relative height difference.

Figure 7 shows the cup geometries in experiment and FEM-analysis for a drawing ratio of β = 1.7. In case of figure 7 (a) the height difference is achieved through curvature deviation of ROC = 2.9 while in figure 7 (b) the blank was positioned with an error of Δx = -15 µm and an ideal tool was used. In figure 7 (c) curvature deviation and blank displacement are combined leading to a reduction of cup height difference. However, a difference in straining of the two sides of the cups wall and wall thickness can be observed. In figure 7 (d) equal parameters were used in experiment.

Figure 7. Cup geometries in FEM-analysis and experiment.
6. Discussion
The results show that curvature deviation and blank displacement have a great impact on the shape of the cups in micro deep drawing. If curvature deviation and blank displacement is considered, it is possible to model this influence in FEM-analysis with good agreement to experimental results.

Judging from the results in FEM-analysis as shown in figure 5 an increasing ratio of curvature leads to an increasing height difference of the cup’s wall. This effect is intensified for higher drawing ratios. If the drawing ratio is increased to $\beta = 1.9$ height deviation of up to $\Delta h = 17 \%$ of the average cup height is observed. Contrarily, the positioning accuracy has a decreasing influence on the shape of the cups. For a drawing ratio of $\beta = 1.7$ height difference is increased by 12 \% but for a drawing ratio of $\beta = 1.9$ height difference is only increased by 7 \% of the average cup height if cups are positioned eccentrically with a deviation of $\pm 10 \mu m$. This can be explained by the different mechanisms that result in cup height difference as shown in figure 7. A constant blank displacement results in initial material surplus on one side of the cup but both sides are strained almost equally. Increasing curvature on the other hand leads to stronger bending at the drawing radius resulting in higher bending and back bending forces and increased straining of the cups wall throughout the drawing process. Therefore height difference increases the more material is drawn into the die, leading to a more pronounced effect for higher drawing ratios.

As shown in figure 6 cup height difference resulting from curvature deviation can be reduced by blank displacement if blanks are positioned towards the side of the die with minimum curvature. If the displacement is chosen correctly it is possible to reduce the cup height difference completely. However, due to the increasing effect of curvature deviation for higher drawing ratios this cannot be achieved by a constant blank displacement instead the displacement has to be adjusted for the given drawing ratio. While cup height difference can be reduced, both sides of the cups wall are still strained differently as can be seen in figure 7 (c). This leads to a difference in work hardening and wall thickness depending on the angular position. Therefore, the effect of curvature deviation cannot be fully compensated by blank displacement.

7. Conclusion
In the reported work the influence of blank displacement and curvature deviation on the forming process of micro cups has been investigated. It can be concluded that the effect of curvature deviation cannot be compensated by intentional blank displacement. While cup height difference resulting from curvature deviation can be reduced, a difference in straining, work hardening and wall thickness remains in the deep drawn parts.

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References
[1] Geiger M, Kleiner M, Eckstein R, Tiesler N, Engel U. Microforming. CIRP Annals - Manufacturing Technology 2001; 50(2): 445–62
[2] Masuzawa T. State of the Art of Micromachining. CIRP Annals - Manufacturing Technology 2000; 49(2): 473–88
[3] Apple Inc. Q4 2016 Unaudited Summary Data; 2016. Available from: URL: http://images.apple.com/de/pr/pdf/q4fy16datasum.pdf.
[4] Lange K. Handbook of metal forming. 1st ed. Dearborn, Mich.: Society of Manufacturing Engineers 1995.
[5] Gau J-T, Principe C, Wang J. An experimental study on size effects on flow stress and formability of aluminium and brass for microforming. Journal of Materials Processing Technology 2007; 184(1-3): 42–6

[6] Hu Z. Analyse des tribologischen Größeneffekts beim Blechumformen. Bremen: BIAS 2009.

[7] Vollertsen F, Biermann D, Hansen HN, Jawahir IS, Kuzman K. Size effects in manufacturing of metallic components. CIRP Annals - Manufacturing Technology 2009; 58(2): 566–87

[8] Hu Z, Walther F, Vollertsen F. Forming tools in micro deep drawing – Influence of the geometrical tolerance of forming tools on punch force in micro deep drawing. wt Werkstatt Technik online 2009; (H 11/12): 814–9.

[9] Behrens G, Trier FO, Tetzel H, Vollertsen F. Influence of tool geometry variations on the limiting drawing ratio in micro deep drawing. Int J Mater Form 2016; 9(2): 253–8

[10] Köhler B, Bomas H, Zoch H-W, Stalkopf J. Werkstoffprüfung an Mikroproben und -halbzeugen. MP 2010; 52(11-12): 759–64

[11] Grüner M, Merklein M. Determination of friction coefficients in deep drawing by modification of Siebel’s formula for calculation of ideal drawing force. Prod. Eng. Res. Devel. 2014; 8(5): 577–84