Analysis of Size Effects in Micro Sheet Forming

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The main objectives of the project "Relevance of Size Effects in Micro Sheet Forming" are the development of methods for characterising micro deep drawing processes with adequate consideration of size effects and the design of micro deep drawing processes with integration of material and process variability. Different initial tasks can be deduced from these main objectives: Determination of limits of classical numerical methods like FEM (Finite Element Method) in the design of micro deep drawing processes and adequate determination of material properties and relevant process parameters such as flow stress of metal foils, friction, etc. as well as their variance.

1 Introduction

Micro deep drawing processes are strongly influenced by process disturbances resulting from varying tribology and material properties as well as other boundary conditions [1]. Also size effects can change process variables, e.g. flow stress decreases with increasing fraction of surface grains [2] **(Fig. 1)**.

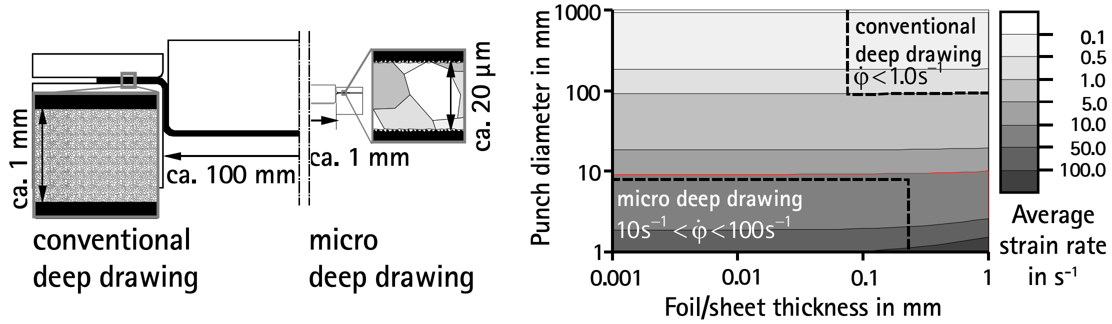

Fig. 1: left: difference between conventional deep drawing and micro deep drawing
right: average strain rates in flange for punch velocity of 100 mm/s

Effects influencing scaled down deep drawing process can be divided into three types assuming the use of the same material in each case.

1. Effects can result from incorrectly scaled processes in reference to similarity theory [3], e.g. punch velocities of conventional deep drawing and micro deep drawing are in the same range of 100 to 300 mm/s [4]. Strain rates increase with a decrease in the geometric scaling factor, if the punch velocity is constant. Thus stresses and forces increase when using materials with rate dependent flow stresses **(Fig. 1)**. These effects can be eliminated by adjusting the process according to similarity theory.
2. Effects influenced by process factors are termed effects of the first type [5], if these factors are not scalable in reference to similarity theory. For example a scaled process

with a similar temperature field with respect to heat conductivity demands a different time scale than a process with similar strain rates with respect to rate dependent flow stresses. The incongruity of the two time scales causes size effects of the first type. These size effects often result from the increase in surface-to-volume ratio by geometric scaling to smaller sizes [5].

3. If internal microstructure dimensions such as the grain size influence process variables, the resulting effects are called 'size effects of second type' according to [5].

Effects in 1 and 2 can be described in FE modelling under usage of classic continuum mechanics, which are integrated in commercial FE-software. All effects described above can be in the same range of the material and process variations or can cause them. Thus, variances of material properties and process parameters will be measured in future works. Tools, measurement fixtures and FE models are prepared and initial tests are performed.

2 Preparations

2.1 Tool concept

Fig. 2: left: deep drawing tool with tool set for 4.0 mm punch diameter
right: tool set for 1.0 mm punch diameter

A micro deep drawing tool **(Fig. 2)** was designed for adequate analyses of size effects. The tool demands the following requirements.

- An easy change of tool sets enables a geometric scaling of active surfaces for deep drawing, e.g. punch and die. The table in **Fig. 3** shows geometric parameters of active tool parts. Also drawing radius r_d and punch edge radius r_p are scaled geometrically.

	Normalised to punch radius	Scaling factor λ			
		1/8	1/4	1/2	1/1
Punch diameter d_0	1/1	1.00 mm	2.00 mm	4.00 mm	8.00 mm
Foil thickness s	3/80...4/100	0.04 mm	0.08 mm	0.15 mm	0.30 mm
Blank diameter D_0	2	2.00 mm	4.00 mm	8.00 mm	16.00 mm
Die radius D_1	43/40	1.08 mm	2.16 mm	4.30 mm	8.60 mm

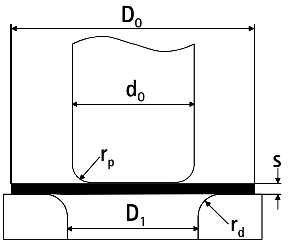

Fig. 3: Tool data table: geometry parameters of tool sets

- A high and above all reproducible accuracy of positioning of the circular blank is guaranteed by direct foil cutting above the deep drawing position. The circular blank falls onto the deep drawing die controlled by the cutting die **(Fig. 4)**.

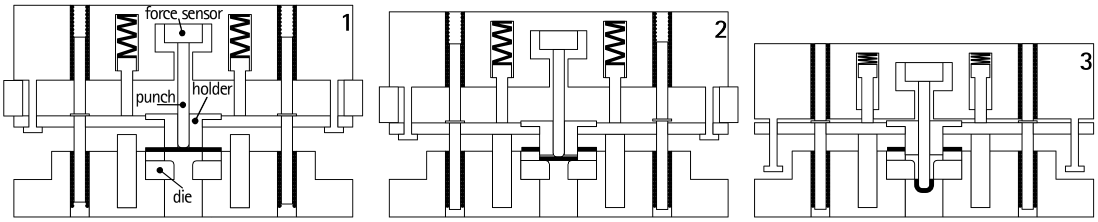

Fig. 4: Colocated cutting and deep drawing processes

- A force sensor is placed above the punch in line with the force direction. Forces resulting from the friction at the outer four guide pillars have no effects on measured punch forces. A low force results from friction bushing of the punch in the cutting die.
- The punch force is measured by a piezo electric force sensor, which offers a maximum measurement range of +/-5 kN and a sensitivity of –4.3 pC/N with high linearity in different measurement ranges. A loss of electric charge (drift) can affect measurements with a punch velocity of less than 0.1 mm/s [6].
- Spring forces above 1 kN fix the blank holder. A small gap exists between the foil and blank holder. The gap can be changed by using thin plates.

It is necessary to measure the forces resulting at the bearing of the punch in the blank holder. To achieve this, punch forces of the deep drawing process were measured without foil for tool sets with 4 mm and 8 mm punch diameter. The bearing forces are from 14 N to 24 N for the tool set with 4 mm punch diameter. The maximum punch force is about 750 N for this tool set when using CuZn37. The force fraction of punch bearing is 3.2%. The bearing forces are below 1 N for the tool set with 8 mm punch diameter. This force fraction will increase for tool sets with 1 mm and 2 mm punch diameter, due to the smaller forming forces. In future works an accurate measurement of these bearing forces is planned.

2.2 Material

Brass (CuZn37) was used for first experiments. It is avaiable in foil thicknesses from 0.04 mm to 0.3 mm. This material is characterised by its good deep drawability. Therefore CuZn37 foils can be used for testing the experimental setup of the deep drawing process and measurements of geometry. In addition the microstructure, in particular the grain size, can be changed by heat treatment.

The use of Fe with 3% Si (FeSi3) is planned in cooperation with the Chair of Materials Science: Fundamentels and Methodology (Lehrstuhl für Werkstoffwissenschaften/Methodik, WWM) at Saarland University. Average grain sizes larger than 1 mm can be achieved by heat treatment [7].

2.3 Measurement of tool and cup geometry

a) Cups

The possibility of determining diameter, cup height and wall thickness as a function of the rolling direction depends on the size of the cup to measure and its possibility of handling. The cups from the tools with the punch diameters of 8 mm and 4 mm can be measured with measuring instruments provided with calliper **(Fig. 5)**.

Fig. 5: Measurement of wall thickness depending on the angle to rolling direction and cup height (for better representation shown with a halved cup), similar devices exist for bottom end radius area

This kinds of measuring instruments offer an accuracy of 1/1000 mm and need no complex sample preparation which may damage the cups. For the analysis of the smaller cups (punch diameter 2 mm and 1 mm) optical measuring instruments will be used.

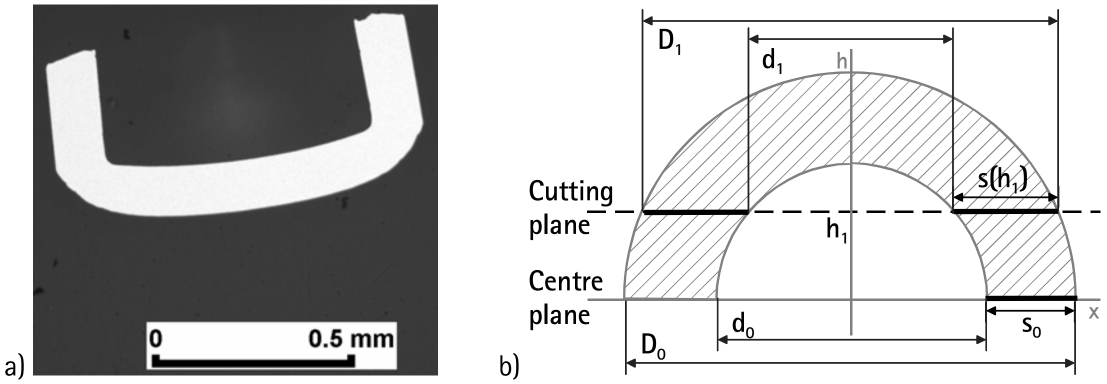

Fig. 6: a) Cup cut at the centre plane (industrial sample)
b) Error made by deviation

Following a complex preparation, the cups are cut in the middle and the wall thickness will be measured with a microscope **(Fig. 6a)**. If there is a deviation h_1 between the centre plane and the cutting plane the real wall thickness can be calculated from the measured wall thickness in the cutting plane and the outer cup diameter D_0 as follows.

Real wall thickness

$$s_0 = \frac{1}{2}\left(D_0 - \sqrt{D_0^2 - D_1^2 + d_1^2}\right)$$

Relative deviation error

$$\Delta s_{rel} = \frac{s(h_1) - s_0}{s_0} \cdot 100 \quad [\%]$$

In case of the smallest cups (punch diameter = 1 mm, sheet thickness = 0.04 mm) there is a relative deviation error of $\Delta s_{rel} \approx 1.9\%$ for a deviation of $h_1 = 0.1$mm.

b) Deep drawing tool

In the order of magnitude regarded in this case, tight production tolerances can affect strongly the deep drawing process. Therefore the accurate knowledge of the tool geometry is required. In this case an interferometer provides the opportunity of measuring punch and die [8] **(Fig. 7).**

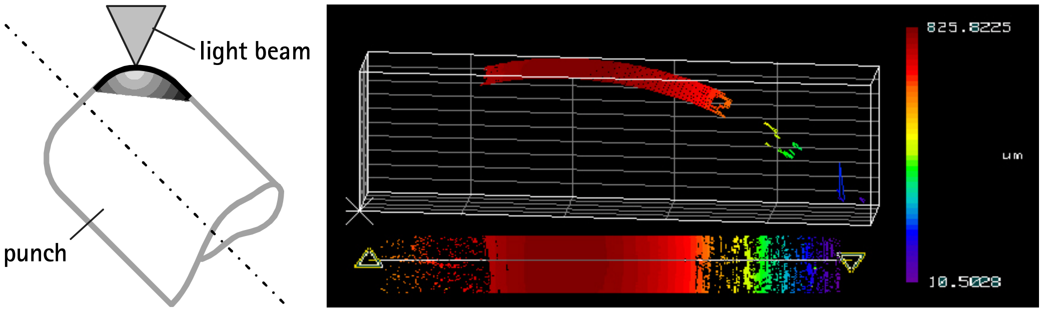

Fig. 7: Measurement of punch edge with the interferometer

The measured tool contour can be fed into the simulation. With this method it could be shown that there were no considerable differences between the actual and the design geometry of the 8 mm punch and its die. But the 4 mm punch showed a deviation of up to 0.06 mm in the punch edge radius (compare tool data table in **Fig. 3** with **Fig. 8**).

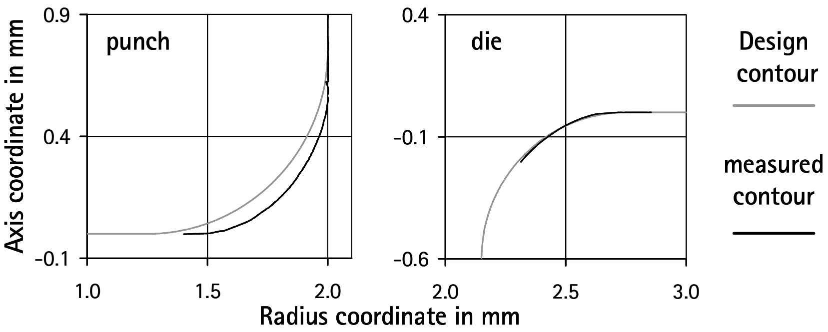

Fig. 8: Comparison between actual and design contour (tool set: 4 mm punch diameter)

2.4 Simulation

"Classic" continuum mechanics is integrated in available commercial FE software. This software can be used to determine effects resulting from incorrect scaling and size effects of the first type. First FE models and parameter variations were prepared and tested. These models will be used for determining size effects of the second type.

Most metallic sheets and foils have anisotropic plastic material properties, so a three-dimensional model is required. A two-dimensional model can be used for fast estimation and large parameter variations to avoid high costs of computing time. Thus a three-dimensional explicit model with solid elements and an implicit two-dimensional model was created in ABAQUS.

Analyses of convergence in consideration of sheet discretisation were made and showed that no appreciable changes in force and sheet thickness were observed, if more than four elements are used over the sheet thickness. Also a validation between 2D implicit and 3D explicit solutions showed small differences of about 4.7% in sheet thickness. A punch speed of 10 m/s [9] was used for explicit simulation by using the same rate-independent material properties in 2D and 3D simulations.

3 Current Results

3.1 Deep drawing results

Results of initial tests with CuZn37 and punch diameters of 4 mm and 8 mm can give insight into relevant influencing process variables in micro deep drawing. These tests are important to determine typical boundary conditions of the deep drawing process. Deep drawing of CuZn37 foils with a thickness of 0.15 and 0.3 mm as delivered generates typical curves until a normalised drawing depth $\Delta h/d_0$ of 0.75 **(Fig. 9)**. The second maximum of punch force F results from ironing. It is caused by a thickened sheet drawn through the smaller gap between punch and die. Simulation results show a similar effect **(Fig. 12)**.

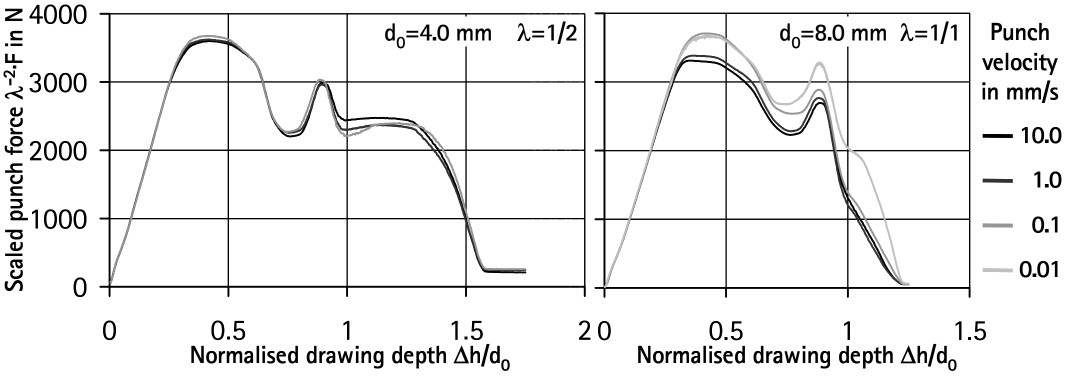

Fig. 9: Punch force versus normalised drawing depth

A variation of the punch velocity gives information about influences of plastic rate dependencies or friction conditions. The first maximum punch force is a representative value of the punch force drawing depth curve **(Fig. 10)**.

The results of a velocity variation with 8 mm punch diameter shows a decrease of 400 N (11%) for maximum punch force by increasing punch velocity from 0.1 to 10 mm/s, which can currently not be explained. This decrease is not effected by a drift of the piezo electric force sensor, since it is larger than a theoretical maximum drift of 2.6 N reached at maximum punch force. Also the flow stress of CuZn37 tends to increase with a change in the strain rate from $3.5\cdot10^{-4}$ 1/s to 0.375 1/s as measured in tensile tests. Average strain rates of the velocity variation are between $2.4\cdot10^{-3}$ 1/s and 2.4 1/s for deep drawing tests with 8 mm punch radius.

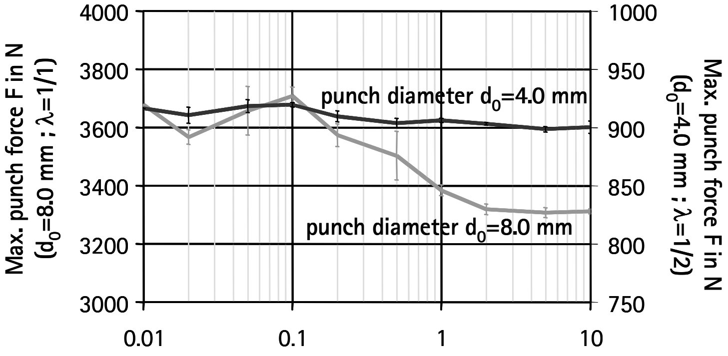

Fig. 10: Maximum punch force (deep drawing) versus punch velocity

3.2 Tensile tests and flow stress curves

Tensile test specimens have been eroded and tested for the determination of material properties as specified in DIN EN 10002-1 [10] **(Tab. 11)** and also at higher strain rates up to 0.375 1/s.

Tab. 11: Results of tensile tests

Sheet Thickness	Yield strength $R_{p0,2}$	Tensile strength R_m	Failure strain A_{50}	Max. true strain φ
0.30 mm	406 N/mm^2	462 N/mm^2	16.3 %	0.12
0.15 mm	427 N/mm^2	460 N/mm^2	11.8 %	0.09
0.08 mm	272 N/mm^2	410 N/mm^2	28.0 %	0.24

A reliable approximation becomes difficult due to the small true strain values reached in tensile tests, because even small errors can have a large influence. The error increases by the following extrapolation of the flow curves, which is necessary in this case as true strains of $\varphi = 0.69$ are demanded for a drawing ratio of $\beta = 2$. The small strain values combined with the different states of stress [11] for the tensile test and deep drawing process lead to high uncertainties when using the determined flow curves in the simulation.

3.3 Simulation results

Differences between simulation results and experimental results can show influence of size effects or effects caused by incorrect scaling of boundary conditions, if the simulation of one reference size is calibrated by experimental results. A flow stress curve measured by static tensile tests of CuZn37 and approximated with LUDWIKs law (k_f=438 N/mm^2 + 426 N/mm$^2 \cdot \varphi^{0.641}$) [12] is used as input data for simulation. The simulation is computed for elastic and plastic forming under static conditions. Thus results of simulated punch force are similar for 4 mm and 8 mm punch diameter by a force scaling factor of 0.25. The simulation results agree nearly with the experimental results until a normalised drawing depth of 0.7 **(Fig. 12)**. The difference between the simulated and experimental second force maximum results from the larger die height used in simulation **(Fig. 3, Fig. 12)**.

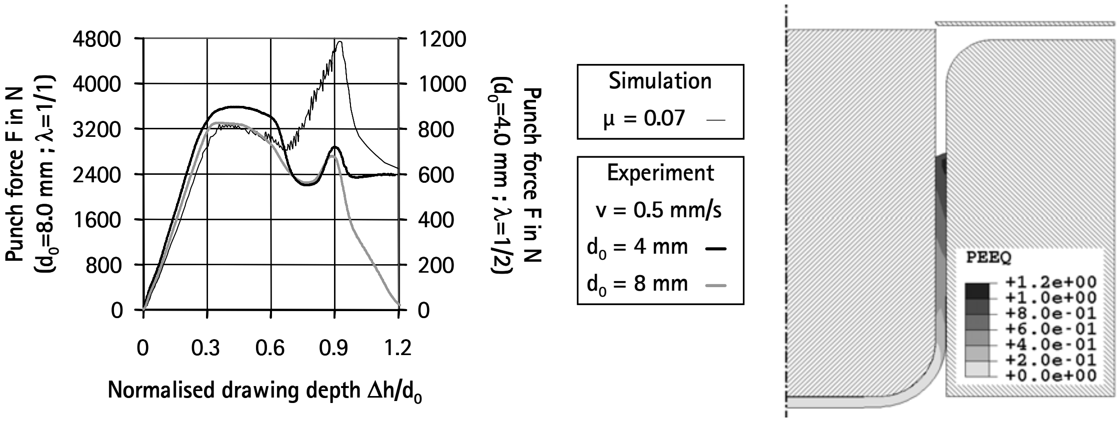

Fig. 12: left: punch force versus drawing depth / right: plastic equivalent strain

4 Critical Review

A precise experimental set-up for micro deep-drawing has been developed and first trials were made by using the two largest tool sets (punch diameter 8 mm and 4 mm). Initial curves showing punch force versus drawing depth curves could be determined in the experiment and compared with results from the ABAQUS/implicit simulation model. These provisional experimental results show good agreement with simulation results. The planned analysis of cup geometry in simulation and experiment as well as specific variations of parameters (e.g. tool geometry, tool velocity, material properties) is based upon these data. They also show that an accurate determination of boundary conditions like friction or material properties is important for the measurement of size effects. Through cooperation of the LWP with WWM and ENSAM the characterisation and discription of material behavior should be improved by the analysis of the material FeSi3.

5 Literature

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