In-Situ-measurement of restraining forces during forming of rectangular cups

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Abstract. This contribution introduces a new method for evaluating the restraining forces during forming of rectangular cups with the goal of eliminating the disadvantages of the currently used scientifically established measurement procedures. With this method forming forces are measured indirectly by the elastic deformation of die structure caused by locally varying tribological system. Therefore, two sensors were integrated into the punch, which measure the restraining forces during the forming process. Furthermore, it was possible to evaluate the effects of different lubricants showing the time dependent trend as a function of stroke during the forming of the materials DP600 and DC04. A main advantage of this testing method is to get real friction corresponding data out of the physical deep drawing process as well as the measurement of real acting restraining forces at different areas of the deep drawing part by one single test. Measurement results gained by both sensors have been integrated into LS-Dyna simulation in which the coefficient of friction was regarded as a function of time. The simulated and deep drawn parts afterwards are analysed and compared to specific areas with regard to locally measured thickness of part. Results show an improvement of simulation quality when using locally varying, time dependent coefficients of friction compared to commonly used constant values.

1. Introduction
Models simplifying physical effects are still necessary to measure effects of friction in sheet metal forming processes. The disadvantages of all model tests performed are the simplifications of the deep drawing process that are necessary to measure the restraining forces. The majorities of the known tests for evaluating restraining forces in deep drawing are limited to a specific part of the flange or die radius and do neither take into account friction impact of entire part nor the occurring interdependencies. Commonly performed strip drawing tests do not take into account surface enlargement of material nor include the measurements of tangential compression stresses during deep drawing processes. These factors indeed do change the tribological system and to date it was impossible to describe the entire system using only one single test.

Increasing demands on weight saving in car body industries result into manufacturing and processing of high strength steels because less material is required for the same level of strength [1]. Additional to that, the process window has to be extended by modifying the friction [2] to ensure proper manufacturing of such components made of sheet metal. To model the occurring tribological system, a broad knowledge base of physical interdependencies of the influencing factors is necessary. Therefore, many simple model tests were performed in the past in the field of sheet metal forming to gain knowledge about friction and corresponding modelling for simulation objectives. Commonly
used tests are mentioned in [3] and represent a single part of the tool, e.g. the flange. The tests are designed in a way in which they can be controlled easily and single parameters can be determined. Thus, they present substantial deviations from the deep drawing processes [4]. The simplifications of the process are necessary to measure the occurring restraining forces directly, but lead to a loss of information and decrease the quality of the simulation. To classify the model tests, [5] defines six categories, in which the load condition of the test is closer to the real component with decreasing number of category. The load condition in the experiment has to be as close to the real component as possible to improve the prediction accuracy of the experiment. To measure restraining forces during a real deep drawing process [6] uses 3 component load cells that are integrated into the die of a deep drawing tool. [7] used same 3 component load cells and a segmented blank holder, where the restraining force of the complete segment was recorded. Unfortunately these methods for in-situ measurement of restraining forces are not capable of being integrated to series production tools.

![Friction Force Sensor](image1.png)

**Figure 1.** 3D-friction force sensor to measure local restraining forces [6].

![Segmented tool with four integrated 3D-force load cells](image2.png)

**Figure 2.** Segmented tool with four integrated 3D-force load cells to measure restraining forces [7].

Due to high cost for performing friction tests and high engineering effort in terms of proper transfer of measured friction values into FEA codes of today, the automotive industry mainly uses generalised and constant coefficients of friction. Objective of this paper for that reason is to present a new method for in-situ-measurement of restraining forces during forming. Lubricants having different viscosities, drawing tests performed at different drawing speeds, and different materials are measured in a real deep drawing process and modelled in FEA within the scope of this work. Additionally, two different drawn sheet metal components were selected and analysed. To evaluate the quality of the simulation, sheet thickness reduction occurring in both parts were compared between simulation and experiment.

2. Experimental procedure and measurement method

2.1. Experimental procedure and setup

Deep drawing experiments for determining occurring restraining forces were performed without any part failures based on using rectangular cup geometry. AIDA servo press machine at IFU with a maximum ram capacity of 6300 kN was used for this. The tool can be used for single strokes or continuous test objectives. Used material (deep drawing steel DC04) was chosen with a thickness of 0.7 mm and a high strength steel (DP600) was chosen with a thickness of 1.2 mm. Amount of lubrication was given by 1.5 g/m² of CLF65E (Raziol) with a viscosity of 65 mm²/s at 40°C and CLF400E (Raziol) with a viscosity of 400 mm²/s at 40°C. Drawing tests were processed with two different ram velocities (3 strokes/min; 9 strokes/min). The sensors were integrated into the corner and in middle of straight area of the punch. All tests were performed at room temperature.
2.2. Introduction of measurement method

The changeable restraining forces are measured indirectly by the elastic deformation of the tool caused by different tribological systems. Therefore, the piezoelectric sensor (Kistler Typ 9247A), a longitudinally sensitive pin, was used. The pin is mounted by an M5 thread and the end of the sensor transfers the strain of the surrounding material to the quartz sensing element. The electrical charge output is proportional to the change in mechanical strain [8]. The elastic deformation of the punch is dependent on the occurring drawing force. According to [9] this force can be determined by Siebel’s formula

\[ F_{\text{total}} = F_{\text{id}} + F_{\text{fric,BH}} + F_{\text{fric,DR}} + F_{\text{bnd,bckbnd}} \]  

with

- \( F_{\text{id}} \) = ideal forming force,
- \( F_{\text{fric,BH}} \) = restraining force resulting from friction by blank holder,
- \( F_{\text{fric,DR}} \) = cable friction force at die radius,
- \( F_{\text{bnd,bckbnd}} \) = force from bending and back bending.

In this equation, \( F_{\text{id}} \) and \( F_{\text{bnd,bckbnd}} \) are dependent on geometrical and material properties, \( F_{\text{fric,DR}} \) and \( F_{\text{fric, BH}} \) are dependent on geometry, blank holder force, material properties and coefficient of friction. When using same testing parameter, except variations in speed or lubrication, measured changes are only dependent on changes in the tribological system. The main advantage of this measurement method is that no direct contact of sensor and blank occurs and as a result of that the restraining forces are not influenced and changed by the measuring method. Figure 3 shows the integrated sensor positioned with a 45° degree orientation to drawing direction. Figure 4 shows the graph of the measured sensor signals for different tribological systems. To calibrate these sensor signals and use them as coefficient of friction in simulation, a measured curve was modified with a factor to fit sheet thickness from simulation to the experimental measured. The same factor was used for all variations in tribological system.

![Figure 3. Punch with integrated sensor to measure restraining forces](image)

![Figure 4. Measured sensor signals for different lubricants](image)

3. Numerical Procedures

The deep drawing process of rectangular cups was modelled using the FE-software LS-Dyna to compare any changes of the sheet thickness between experiment and simulation. Flow curves were determined in a uniaxial tensile test using a Zwick tensile test device. Figure 5 shows the extrapolation of the flow curves using the Hockett-Sherby criterion. Additional information on recording of such flow curves can be found in [10].

Different geometrical areas of the tool, punch, die, and blank holder are modelled in segments in order to integrate different coefficients of friction into simulation model (Figure 6). LS-Dyna was used as FE-Solver, FE-Models first were built up in DynaForm 5.9 and modified with LS-Prepost 4.1. Drawing speed, sheet metal thickness and blank holder pressures were recorded with measurements in the real deep drawing process and were set equivalent in simulation. All time steps are multiplied with the factor 0.01, which results into shorter simulated drawing process and reduces simulation time.
LS-Dyna does not allow the integration of time dependent coefficients of friction, but the program supports a thermal friction option which uses temperature dependent coefficients of friction. Therefore, a coupled thermal-mechanical simulation was built up, in which the tool and blank are heated continuously, and thermal friction coefficients were defined ($\mu(\theta) \rightarrow \theta(t) = \mu(\theta(t))$). The speed of ram and punch was set according to the real deep drawing tests of press machine in order to consider the speed and movement of punch realistically and to assign measured sensor signals to the right time step of the simulation. The measured sensor signal at corner and straight side of the punch were used as temperature dependent coefficient of friction for the corresponding part of the tool.

The validation of integrating time dependent coefficients of friction is shown in Figure 7. An abstracted strip drawing test was modelled in LS-Dyna with the same speed profile of AIDA servo press ram during drawing. The temperature is increasing continuously from 20°C to 40°C to assign a specific coefficient of friction to each temperature. The force in x-direction was evaluated to prove that the coefficient of friction is changing in the required way.

4. Experimental and numerical results
Ten measuring points were chosen along two lines to compare simulation with experiment. First line diagonal from the part corner of the rectangular cup; second is set along the straight side. The sheet thickness was measured tactile, initial sheet thickness of DC04 was 0.70 mm; DP600 had a thickness of 1.2 mm. To show the performance of a simulation with integrated coefficients of friction that were measured in a deep drawing process, distribution of sheet thickness of cups deep drawn with different amounts of lubricant was compared to corresponding simulation being performed with the generalised coefficient of friction as well as to executed, real experiments (Figure 8). A satisfactory correlation could be achieved especially for the straight area. Lubrication reveals a higher affection on thinning in the straight than in the corner area. The different lubrication and the resulting tribological system is not that explicit due to the occurring tangential compression stresses.
Figure 8. Simulated and experimentally measured distribution of sheet thickness for different lubricants at different part areas (solid lines: real deep drawing, interrupted lines: simulation).

Figure 9 shows the influence of variation of drawing velocities on sheet thicknesses. The velocities used were measured in the real forming process at 3 and 9 strokes per minute, which results into an average speed of $v_1 = 45 \text{ mm/s}$ and $v_2 = 135 \text{ mm/s}$. Distribution of sheet thickness when simulated with measured sensor signals shows a good correlation to deep drawn experiment in comparison to a generalised coefficient of friction. Especially along the straight area of part perimeter, sheet thickness was predicted exactly. The reduction of thinning, when raising the drawing speed, is caused by the hydrodynamic effects that reduce the coefficient of friction. Occurring deviation at measuring points 8 and 9 of the corner area develops during the bending of the sheet material and is mostly affected by the material model. Finally coefficient of friction is not the most dominant factor due to the small relative movement between sheet material and tool.

Figure 9. Simulated and experimentally measured distribution of sheet metal thickness for different drawing velocities at different part areas (solid lines: real deep drawing, interrupted lines: simulation).
In order to ensure that the sensor signals are performing and working independently from the material, the high strength steel DP600 also was analysed in a real deep drawing process as well as in simulation. Figure 10 shows the deviation from initial sheet thickness in percent to compare the two different materials with different initial sheet thicknesses. The deviation corresponds very well for the two areas, corner and straight, as well as for both materials. The percentage thinning of points 7 to 9 is lower for DP600 in comparison to DC04. This is caused by the higher yield strength of the DP600 sheet material. The deep drawing experiments were performed for both materials with the same blank holder force of 275 kN. Due to the higher strength, higher loads can be carried and a smaller thinning occurs.

![Figure 10](https://example.com/figure10.png)

**Figure 10.** Simulated and experimentally measured change of initial sheet thickness for DP600 and DC04 at different part areas (solid lines: real deep drawing, interrupted lines: simulation).

5. Conclusions
Deep drawing tests were performed for different tribological systems with rectangular cup geometry. Restraining forces were measured in-situ for two geometric areas and integrated in a LS-Dyna simulation. The integration was feasible with LS-Dyna using a thermo-mechanical simulation with defined heated tool and blank as well as the thermal friction option where a specific coefficient of friction is attached to each temperature. This procedure allows the integration of time dependant coefficients of friction. Die, punch and blank holder were modelled segmented and measured signals were assigned to the according area. The feasibility of the novel in-situ measuring method of restraining forces was proved by a comparison of material thinning with rectangular cups. Results show that effects of lubrication, drawing velocity and sheet material are reproducible in FE-simulation when using the mentioned method. Results show, that the use of varying coefficients of friction improves the prediction quality of simulation in matters of thinning compared to the use of constant values.

Further investigations will deal with additional part areas as well as sensors in the die to evaluate the friction forces for specific geometric areas. Furthermore, a model to calculate the coefficient of friction dependant on the measured forces will be developed. The comparatively easy integration of the sensor into a deep drawing tool offers an immense potential for in-situ-monitoring of the friction forces and to detect deviations during a production process.
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