Influence of varying sheet material properties on dry deep drawing process

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Abstract. Deep drawing is one of the most important processes in sheet metal forming. Conventionally, lubricants are used to reduce friction and wear. Demands for increased sustainability, environmental protection and resource efficiency motivate the realization of lubricant-free forming processes. The direct contact between tool and workpiece during dry deep drawing results in challenging tribological conditions, which cause an increase in friction and wear. Friction-reducing surface modifications of the tool such as carbon based coatings are being developed for the adaptation of the tribological conditions. The aim of this work is the simulation-based analysis of the stress spectrum for varying sheet properties for the qualification of wear-reducing surface modifications for a wide range of applications. By a simulation model for a rectangular cup, the influence of different batches of steel and aluminum materials with varying friction coefficients and mechanical properties is investigated within the framework of variant simulations. The tribological conditions in the simulation are described on the basis of friction coefficients from the strip drawing test. From the simulation results, the applicability of surface modifications for dry deep drawing is being evaluated depending on the sheet specific properties.

1. Introduction

Deep drawing is one of the most widely applied sheet metal forming processes. Common deep-drawn parts are produced, for example, in the automotive, aviation and household appliance industries. Conventionally, lubricants are applied as a separating layer in the forming zone between tool and sheet to reduce friction and wear during production of such parts [1]. Growing ambitions for resource efficiency and sustainability promote the abandonment of environmentally harmful lubricants and associated additional process steps such as washing and drying operations [2]. In order to realize such dry forming processes and effectively adapt to the changed tribological conditions, diamond-like carbon (DLC) coatings are applied to the tool surfaces [3]. DLC coatings like amorphous hydrogenous carbon (a-C:H) coatings and tetrahedral hydrogen-free amorphous carbon (ta-C) coatings have a high hardness and chemical inertness, which considerably reduces friction and adhesive wear during dry metal forming. Prior studies revealed this fundamental correlation for different steel and aluminum alloys in various laboratory tests. Deep drawing experiments with DLC coated tools confirmed the reduction of resulting forming forces as well as an increase in the part quality and tool life in comparison to uncoated tool surfaces [4]. Furthermore, the level of friction encountered with coated
tools depends on different parameters such as the tool roughness and the chemical composition of the sheet material [5]. The influence of further sheet properties like different sheet textures and roughnesses is thereby primarily known within lubricated conditions. In order to fully understand and enable dry deep drawing processes for a wide range of applications, the influence of varying sheet properties in dry contact has to be investigated deeper. In this study, the influence of changes in the topography and mechanical properties of the sheet material against its tribological behavior during dry contact with DLC coatings is analyzed. As a model process, deep drawing of a rectangular cup was selected for numerical and experimental tests. In order to quantify the level of friction for the numerical analysis, flat strip drawing tests were conducted.

2. Testing procedure
In order to investigate the influence of changes in the topography and mechanical properties of the sheet materials against its tribological behavior during dry contact with DLC coatings, strip drawing and deep drawing tests were conducted. Figure 1 shows the test parameters for each test setup and evaluation criteria.

![Image of test parameters, setup, and evaluation criteria]

Figure 1. Methodology of investigation

In order to analyze the effect of different topographies on its tribological behavior and to define friction coefficients for the numerical analysis, flat strip drawing tests were conducted for ta-C and a-C:H tool coatings for each sheet material under the same process conditions as in the deep drawing tests. The applied contact pressures of 4.5 MPa for DC04 and 1.5 MPa for AA5182 represent appropriate values for dry deep drawing of failure free rectangular cups [4]. By means of a numerical analysis, the influence of different sheet material properties and friction coefficients on the resulting maximum forming forces is investigated in a full factor experimental design. This provides information about the effectiveness of each single parameter and whether a change in the coefficient of friction due to changes in the sheet topography or a change in the mechanical properties due to batch fluctuations has a greater influence on the deep drawing process. In this context, the forming force serves as a representative process variable for evaluating the deep-drawability of the sheets and the tribological performance of the tool coatings. Other process variables, such as the distribution of sheet thickness or the true stain, are not discussed in this study and are subject of further investigations. In order to evaluate the transferability of the results from the numerical investigations to real deep drawing processes, experimental tests for one variant of DC04 and AA5182 were carried out and the force-stroke curves were compared.

2.1 Materials and coatings
The influence of changes in the mechanical properties and surface topography of various sheet materials on its tribological behavior during dry contact with DLC coated tools is analyzed for ta-C and a-C:H coating systems. The structure and application of both coatings are presented in [5]. The coatings were deposited on the tools made out of the cold working steel X155CrVMo12 (1.2379) with a hardness of 60 HRC for suitable coating. The a-C:H coating is deposited in a hybrid PVD/PECVD coating process. The ta-C coating is manufactured by a laser arc process with a graphite target. Due to
the fact that the tool roughness has a major influence on the friction conditions in dry metal forming processes [5], the tool surfaces are mechanically treated by polishing after the coating deposition in order to reduce the roughness of the surfaces and to generate comparable roughness levels. Nevertheless, the a-C:H coated surface with an Ra value of 0.013 is slightly smoother than ta-C with an Ra value of 0.020. In order to ensure a transferability of the test results to practical forming processes, sheet metal materials frequently applied in industry were used. The hotdip galvanized deep drawing steel DC04 is used as steel grade. DC04 is usually used for non-safety-relevant or technically demanding component geometries. A frequent field of application is the manufacture of outer skin parts such as sidewall components for car body construction. Furthermore, the aluminum alloy AA5182 is investigated, which is primarily used for invisible body parts due to its tendency to stretcher strain marks. Conclusions about the tribological application behavior under varying sheet metal properties are drawn by evaluating their topography and their mechanical properties. Optical and tactile measurement systems are used to characterize the different sheet topographies. The mechanical properties are recorded in terms of stress-strain curve and the yield surface. In order to eliminate the influence of different chemical compositions of aluminum and steel materials, two different batches A and B for each sheet material were investigated. Each sheet material has a sheet thickness of 1.0 mm. Before tribological tests are performed, all specimen sheets are cleaned with acetone in order to remove the basic lubrication and to ensure dry contact conditions.

2.2 Test setup
The influence of different sheet properties in dry metal forming was investigated in strip drawing and deep drawing tests. The flat strip drawing test is a well-known approach to model and analyze the tribological conditions in the flange area of deep drawing processes. In addition to an appropriate selection of the friction coefficient for the numerical analysis, differences in friction and wear behavior due to varying surface properties are identified. Figure 2 a) shows the principle setup of the strip drawing test.

The test setup contains an upper and a lower friction jaw and a sheet strip located between those. After application of the defined normal force $F_N$ the strip is drawn through the friction jaws. The measured drawing force $F_{\text{Draw}}$ corresponds to the respective upper and lower friction force $F_{FU}$ and $F_{FL}$ for each parameter set. The friction coefficient $\mu$ is determined according to the Coulomb friction law and is proportional to $F_N$ and $F_{\text{Draw}}$. The contact area equals the size of the friction jaws of 55 x 100 mm.

In order to increase the knowledge of varying process conditions during lubricant-free deep drawing depending on the sheet metal, the geometry of a rectangular cup is used in experimental and in numerical tests. The numerical analyses are based on the investigated material properties and resulting tribological behavior of the applied materials. The deep drawing process is schematically shown in figure 2 b). For the experimental and numerical deep drawing of the rectangular cup, a punch front end radius of 5 mm, a corner radius of 18 mm and a die radius of 10 mm were chosen. The blank size is 160 x 130 mm, which ensures a remaining flange of at least 1 mm and a stroke of 30 mm [4].
order to achieve a defined normal pressure the binder applies a constant force at the initial contact. During forming, the punch moves stroke-controlled in z-direction, whereas the die remains at a fixed position. The experimental tests were conducted with the hydraulic press TSP100So from Lasco. The coated tool surfaces have similar roughness values as the friction jaws from the strip drawing test, which enables the transferability of the tribological conditions. For explicit FE modelling of the forming process the FE-software LS Dyna R9.1 is used. The square shell elements have a length of 1 mm. The double symmetry of the workpiece allowed a reduction of the computation time by generating a quarter model. The material model 133 of Barlat 2000 [6] was applied as a yield criterion for each sheet material and batch. Due to relative low stresses in sheet metal forming, the tools made out of 1.2379 are modelled as rigid bodies. The keyword "Forming-one-way-surface-to-surface" is selected to define the tribological contact conditions between the tools and the blank according to the results of the strip drawing tests. As former studies proved [4], using a global friction coefficient determined by the strip drawing test for the simulation delivers very accurate results regarding the punch force and sheet thickness distribution in real deep drawing processes.

3. Results
The results of dry strip drawing as well as deep drawing tests show the difference in the tribological behavior of several sheet properties depending on the tool coating. The investigation broader aims to identify surface modifications which enable dry deep drawing processes for a wide range of materials.

3.1 Sheet material characterization
The investigated sheet materials differ regarding their topographies and mechanical properties. The two batches of aluminum alloys have a typical EDT surface texture. This texture is often used for conventional deep drawing processes because its rough structure with a high proportion of closed empty volume serves as a lubricant reservoir, which enhances the drawability of complex components. Whereas Charge A of DC04 also has an EDT surface texture, Charge B has a PRETEX structure with defined calottes, which aims to increase the closed empty volume in conventional deep drawing compared to EDT [7]. Figure 3 shows the topography and roughness values in the initial state for the applied workpiece materials.

![Topographies of sheet materials](image)

**Figure 3.** Topographies of sheet materials

Based on the topography images and the reduced valley depth Rvk, it can be seen that the calottes of the PRETEX structure protrude deeper into the surface than the craters of the EDT surface. Due to the
different size and distribution of the craters, differences in the real contact area during relative movement are to be expected. With regard to the aluminum materials there is no difference in the type of texture, but Charge B clearly has more pronounced profile peaks and valleys than Charge A. In addition to the Rvk value, this is reflected above all in the reduced peak height Rpk values, which are on average 0.83 µm for Charge A and 1.62 µm for Charge B. In order to consider the sensitivity of dry deep drawing to changes in mechanical sheet properties due to different batches, a material characterization regarding the stress-strain curve and the yield surface was performed. The experimental determination of the initial yield stress was carried out at a plastic elongation of 0.2%. Figure 4 gives an overview of the results of corresponding tensile and biaxial-tensile tests, which are also used as basis for the numerical material model. The repetition number for each experiment was set to n = 3.

Comparing the two materials, the different material properties between the deep drawing steel and the aluminum alloys become obvious. The aluminum alloy has a lower uniaxial and biaxial yield stress than the deep drawing steel. According to the Hockett-Sherby approximation the maximum uniaxial yield stress ranges for DC04 up to 400 and 450 MPa, whereas AA5182 varies at a maximum level around 360 to 385 MPa. Batch B of AA5182 has constantly higher yield stress values than Batch A, whereas the Batch B of DC04 has a lower initial yield stress but at the same time stronger hardening behavior than Batch A.

3.2 Strip drawing test
The results of the strip drawing tests prove that besides the general chemical composition of the sheet material, different surfaces and mechanical properties of the batches also lead to changes regarding their tribological application behavior. Figure 5 shows the results of the strip drawing tests for a-C:H and ta-C coated friction jaws for both batches of the investigated materials. In general, aluminum and steel materials show comparable friction coefficients on average for each coating. As already proven in [8], these friction coefficients are at a significantly lower level than in investigations with non-modified tool surfaces. The a-C:H coating tends to lead to slightly higher friction coefficients for both sheet materials. In general, lower roughness values of coated tool surfaces lead to lower friction coefficients during dry contact [9]. Due to the fact that the a-C:H tool surface has a lower roughness in comparison to ta-C, higher friction coefficients have to be caused by the higher adhesion tendency of

![Stress-strain curve (Hockett-Sherby) and Yield surface (Barlat 2000)](image)

Figure 4. Mechanical properties of sheet materials
a-C:H coatings. This is particularly evident from the increased standard deviation of AA5182 in Charge B, which also showed first signs of wear on the friction jaw.

Considering the batch-related differences in the sheet topographies, the tendency of higher friction coefficients of batch B compared to batch A of AA5182 can be attributed to the higher roughness values as well as the higher yield stress. The increased interlocking of the profile heights leads to an increased resistance during the relative movement, which results in higher friction coefficients. Furthermore, individual particles can be detached from the sheet surface by strong plastic deformations of higher profile peaks and transferred into the contact zone, which additionally enhances adhesive wear. This relationship is equally evident for DC04. The batch with a lower Rpk value and yield stress results in lower friction coefficients. Moreover, the deep craters on batch B of DC04 favor the removal of abrasive particles from the contact zone.

In order to investigate the effect of varying mechanical properties of sheet materials and batches as well as of friction coefficients on the deep drawing process separately and fully factorially, two different friction coefficients were defined to represent two different tribological conditions for each sheet material and batch. The selected friction coefficients depict in the following investigations roughly the difference due to the coating system. The values of 0.15 for ta-C and 0.17 for a-C:H were determined from figure 5 as the average friction coefficient over both sheet materials and batches. In a broader sense, the difference in the friction coefficient of 0.02 can also be assumed as a representation of a change in the tribological conditions due to changes in the surface texture of the sheet metal material.

3.3 Deep drawing test

For a first estimation of the modelling accuracy, experiments with batch B were compared with the corresponding simulation variants for the a-C:H coated tool. Figure 6 shows exemplary force-stroke curves of the experimental investigations compared to the simulation results for each sheet material. A high degree of conformity between the simulation and the experimental tests with regard to the maximum forces can be observed for DC04. The initially assumed average friction coefficient for a-C:H coated tools from the strip drawing test therefore reflect the tribological conditions during dry deep drawing very well. Smaller deviations can only be detected after reaching high drawing depths, which leads to the conclusion that the real hardening behavior is slightly lower than modeled in the simulation. The experimentally determined force-stroke curve of the material AA5182 shows overall lower punch force maxima than modeled in the simulation. Since the curve shape of the experimental and numerical test is identical, the deviations are less due to the material model than to the assumed friction coefficient. This discrepancy may result from the local wear phenomena which occurred in the
strip drawing test and thus led to too high assumed friction coefficients for the simulation. In experimental deep drawing, these wear phenomena could not be detected, which is partly due to the significantly shorter drawing paths in the flange area during deep drawing compared to strip drawing. These deviations have to be considered when interpreting the variant simulations.

Figure 6. Comparison of experimental and numerical results

For each combination within the full factorial numerical investigations, the resulting maximum punch forces were compared and the effects of the main factors were calculated according to the statistical design of experiments (DOE) [10] methodology. By analyzing the resulting maximum forming force for the investigated variants, the effect of each parameter on dry deep drawing processes can be evaluated. Figure 7 shows the resulting forming force from the numerical tests.

Figure 7. Maximum forces during numerical deep drawing test

The choice of the sheet material has the highest effect on the resulting forming force. Due to the higher yield stress of steel materials compared to aluminum materials, the required forming force for the steel material is 12.59 N higher on average. The maximum forming force of 61.56 N is reached for batch B of DC04 and a friction coefficient of 0.17. Furthermore, it can be observed that a change in the friction coefficient of 0.02 has a higher effect on the resulting forming forces than batch-related deviations with regard to the mechanical properties. As derived from the results of the strip drawing tests, this difference in the friction coefficient can be induced by the variation of the sheet surface as well as by the coating system. Regarding the simulated difference in the mechanical properties of the batches, both materials show higher forming forces for Batch B in comparison to Batch A, which is in both cases due to the higher value of the yield stresses showed in figure 4.
4. Conclusion and Outlook
In this study it was shown by means of strip drawing tests that the sheet surface, especially with regard to its topography, has a comparable influence on the friction conditions as a change in the tool coating system. Higher Rpk values of the sheet surface, especially in combination with higher yield stresses of the same sheet material, lead to higher coefficients of friction by an average of 0.02. The a-C:H coated friction jaw reacts more sensitively to sheet-related fluctuations with regard to changes in the tribological conditions in the contact zone due to the higher adhesion tendency compared to ta-C. In order to simulate those variations and to evaluate the influence of material or batch-related changes in the mechanical properties, numerical analyses were carried out. The comparison of the resulting punch forces from the experiment and the simulation confirmed that the investigated correlations from the strip drawing test can be applied to enhance dry deep drawing processes by adaption of sheet material properties. In order to be able to better evaluate resulting effects and potentials of the adaption of the sheet metal, further investigations should focus on the targeted influencing of the surface texture by different surface finishing methods.

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