Improvement of the drawing ratio of the anisotropic material behaviour under near plane strain conditions for DP600 characterized in elliptic hydraulic bulge test

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Abstract. The plane strain condition is one of the most frequent reasons for failure in a deep drawing process. State of the art material models do not consider this strain state in FE simulations. Since there is only the notched tensile test to determine the first principal stress, an improved testing setup is needed to characterize the first and second principal stresses up to high deformations to determine the material behaviour under plane strain conditions. Within this contribution, an innovative testing setup is used, which induces a near plane strain regime in the specimen with an elliptical hydraulic bulge test. Experiments are carried out in rolling and transversal direction for DP600. Based on the experiments, stress and strain based material characteristics are evaluated. For validation of the setup, square cups are deep drawn, which have a plane strain area at the drawing radius which causes cracking under this strain state. Due to the highly directional dependent material behaviour, the drawing ratio can be increased by considering the anisotropic material behaviour by cutting the blank in an optimized position according to the rolling direction.

1. Introduction
A characterization of the material behaviour is essential for dimensioning a forming process. In a deep drawing process, for example, the characteristic strain and stress states are shearing, plane strain and uniaxial tension, while a stretch forming process has a domination of biaxial strain components. Nevertheless, a determination of the forming limits under these conditions is necessary for a numerical mapping of the forming operation. In this context the minimal forming limit under plane strain plays a major role, because the quantity of failure is about 80% for this strain state [1].

State of the art characterization of the forming limits is the Nakajima test [2], which has been introduced in 1968 or the testing procedure proposed by Marciniak and Kuczynski in 1967 [3]. These testing setups have been combined in the standard DIN EN ISO 12004-2 [4]. In these tests, blanks with different geometries are deformed, and the straining is measured with an optical 3d strain measurement device. Investigation of the direction dependent forming limit of zinc sheets has shown cracking in rolling direction starts at a lower major strain than in transversal direction due to the hexagonal closed package of the zinc alloy [5]. For cubic face centred or cubic body centred structures the anisotropy of the formability is limited [5]. However, the standard DIN EN ISO 12004 demands the specimen preparation in the conservative direction with reduced formability which is transversal direction for steel sheet material. Challenging is the influence of friction, due to the contact of the punch with the blank. To counteract this, Banabic et al. performed hydraulic bulge tests with a carrier sheet, in order to reduce the relative movement between carrier sheet and blank [6]. Abspoel et al. [7] only used uniaxial tensile test data for forming limit prediction by defining dependencies to the other
strain states. Xavier et al. [1] performed notched tensile test for a comparison to the Nakajima tests with the result of a reduction of the characterized formability in the notched tensile tests. Performing hydraulic bulge tests with elliptic die, Rees calculated stress components out of the characterized material anisotropy [8]. In contrast to this, Lazarescu calculated the stress components from elliptical hydraulic bulge tests using the resulting curvature [9]. Challenging in the context of strain rate sensitive materials is that the constant punch force or volumetric flow in bulge tests leads to inaccurate material characteristics. For DC06, Jocham has shown that a strain rate variation leads to different material parameters in a hydraulic bulge test [10]. To combine the stress and strain based material characterization, identification of the forming limit is investigated within this contribution by performing uniaxial tensile tests on the left side ($\varepsilon_2 < 0$) of the forming limit diagram. For the right side of the forming limit diagram ($\varepsilon_2 > 0$), a strain rate controlled hydraulic bulge test with different die geometries is used.

2. Material and experimental setups

2.1 Material

Investigations in this contribution are carried out with a dual-phase steel DP600. This material contains two phases, the cubic body centred and the martensitic phase. Due to a high yield strength and a good formability, this alloy is commonly used in component parts which are exposed to vibration such as the carrier.

2.2 Testing setup for material characterization

Material characterization is done under three different conditions: uniaxial stress, equi biaxial stress and plane strain. For the determination of material characteristics under uniaxial stress, tensile tests are performed according to DIN EN ISO 6892-1[11]. Three tests are carried out in rolling and transversal direction, respectively. Beside of the commonly used uniaxial tensile tests, a hydraulic bulge test setup with strain rate control is used for material characterization under multiaxial stress and strain states. By changing the geometry of the die, different stress and strain states can be applied. A round die introduces an equi biaxial strain state in the specimen while an elliptic die (see Figure 1a) leads to a near plane strain regime. Both geometries are used for this material characterization under plane and equi biaxial strain. Material testing under equi biaxial stress state is done with the testing setup according to Suttner and Merklein [14] while tests under plane strain conditions are performed according to the setup from Lenzen and Merklein [13]. For all tests, strain gauging is done with an optical 3d strain measurement device ARAMIS (GOM GmbH, Braunschweig, Germany). For comparability, the testing velocity is set on a constant value of 0.4 %/s for each experiment.

2.3 Setup for square cup deep drawing process

For the experimental deep drawing of square cups, a triple action hydraulic press LASCO Typ TSP 100 So (LASCO Umformtechnik GmbH, Coburg, Germany) with a maximum punch load of 2000 kN and a maximum drawing power of 250 kN is used. The used blank geometry is a square of 185.0 mm length and 147.0 mm width. The used geometry of the punch is depicted in Figure 1. The die radius is 10.0 mm and the punch radius towards the bottom is 5.0 mm.

![Figure 1. Geometry of the die (a) Geometry of the punch (b)](image)

The testing velocity is set to 5 mm/s. For a homogeneous friction between the tool and the blank, the lubricant Multidraw KTL N 16 (Brachthäuser Mineralöle GmbH & Co. KG, Finnentrop, Germany) is used to guarantee a comparable friction coefficient of 0.04 for the DP600 according to the results of
the numisheet benchmark 2008 [14] for steel alloys. Tests are performed in two different directions, the rolling direction (RD) and the transversal direction (TD).

3 Material characterization and verification for the determination of forming limits

The determination of the specific forming limits in this contribution is done with a hydraulic bulge test that is strain rate controlled. This means the deformation rate can be held on a constant value of 0.4 %/s during plasticization and strain rate effects can be reduced. Figure 2a shows the resulting flow curves for the elliptic hydraulic bulge test in rolling and transversal direction. The testing direction is defined as direction orthogonal to the crack. It is visible, that the formability is significant higher in the rolling direction. In transversal direction, the maximum reachable major strain is 0.2. In contrast to this, the maximum major strain in rolling direction reaches 0.31. The measured strain fields in the elliptic hydraulic bulge tests are used to identify the maximum forming limit for each experiment. Therefore, three line cuts with 1.0 mm distance are defined orthogonal to the localized necking zone at the last image before cracking occurs. The resulting line cuts are further evaluated according to the standard DIN EN ISO 12004-2 [4] for Nakajima tests. These forming limit curves are depicted in Figure 2b for elliptic and circular bulge tests. The verification of the testing setup and evaluation is done by Nakajima tests for comparable strain states.

![Figure 2. Direction dependent low curves under near plane strain characterized in elliptic hydraulic bulge test (a) and strain rate controlled forming limits with reduced influence of friction for DP600 (b)](image)

Figure 2b shows the good accordance between the elliptic hydraulic bulge test and additional performed Nakajima tests in the same direction. The direction dependent maximum major strain is on equal level, respectively. For circular hydraulic bulge tests, a slightly lower maximum strain can be reached in bulge tests, which is explained through different measuring frequencies in the different testing setups. This means, the last picture before cracking can be taken in between a range of 0.33 seconds. Due to the equi biaxial pre straining in Nakajima tests, the specimen with 125 mm width leads to a too high minor stain when comparing it to the elliptic bulge tests. Therefore, Nakajima tests with 110 mm width are additionally performed. In this case, the minor strain is slightly below the measured one in elliptic hydraulic bulge test. In general, the progression of the forming limits is comparable to the Nakajima testing results. Therefore, stress and strain based material characteristics can be obtained by the strain rate controlled hydraulic bulge test in one single test. Another advantage of the testing setup is the strain rate control which allows a nearly constant deformation of the specimen until cracking. Figure 3 shows the resulting strain rate in the cracking area over the normed testing time. The evaluation area is circular with 10 mm width around the crack. The resulting strain rates of the von Mises equivalent strain in the hydraulic bulge test show a constant progression of 0.4 %/s until the end the test. Only in the last 20 % of the testing time a slightly increase of the strain rate to 1.2 %/s in maximum is visible. This effect is explained by the localisation of the plastic deformation. The strain rate plots for Nakajima tests for the two near plane strain geometries and a full specimen reveal a significant higher strain rate at the end of the test with more than twenty times higher rates than desired due to the constant velocity of the punch. By increasing the measuring frequency in bulge tests, the strain rate at the last measurement cold further increase over 1.2% /s, due to localized necking with a local higher strain rate in the last 0.33 seconds of the test. Nevertheless, the evaluation of the formability is done according to the standard, which means, the local strain value is
not considered for evaluation. Although, for DP600, investigations of Rahmaan [15] showed that there is no significant strain rate sensitivity in the maximum strain by changing the strain rate in uniaxial tensile tests. Therefore, the Nakajima testing setup can be used as well for this material. Advantage of the strain rate controlled elliptic hydraulic bulge test is the possibility of obtaining information of both, stress and strain dependent material properties in one single test, while in Nakajima tests, only information about strain can be quantified. The stress dependent specifics could be measured in the notched tensile test, but in this testing setup, only the yield stress in the first principal direction can be measured. The second principal stress is not measurable there. Also the forming limits cannot be characterized with sufficient accuracy due to the notch effect, which leads to an early crack initiation at significant lower strains, than reachable in the elliptic bulge test [14]. Hence, the strain rate controlled hydraulic bulge test allows the measurement of parameters for identification of yield criteria and failure criteria in one single test and therefore reduces the amount of tests about 50%.

Figure 3. Resulting strain rate over normed testing time in Nakajima and hydraulic bulge tests

4 Validation with a deep drawing process
The validation of the direction dependent forming limits of DP600 obtained in strain rate controlled hydraulic bulge tests is done with the analysis of the formability of a square cup. Hence, the process is numerically designed, to obtain the necessary information about the direction dependent maximum drawing depth. Afterwards, tests are performed to validate the proposed testing setup.

4.1 Modelling of the deep drawing process
The numerical mapping of the deep drawing process is done with LS-Dyna (DYNAmore GmbH, Stuttgart, Germany). Therefore the punch, the die and the binder have been implemented as rigid shell elements with a mesh size of 0.5 mm. The material parameters have been set to a density of ρ = 7.8 g/cm³ and Young’s modulus E = 210000 MPa for each part, respectively. The element size of the blank is set to 1.0 mm length with five integration points over the sheet thickness of 1.0 mm. The material of the blank is mapped with the Yld2000-2d criterion from Barlat et al. [16] with the model parameters given in [11]. Though, the yield stress under plane strain is used to calibrate the yield locus exponent.

Material hardening is implemented via the hardening rule Hockett-Sherby with the parameters a = 2107.85, b = 1857.49, c = 0.583 and q = 0.323. The used contact conditions i.e. the friction coefficients are set to 0.04 according to an oiled surface. Also, the other parameters are set equally to the described testing setup in chapter 2.3 to guarantee the comparability of the numerical and experimental results. The computation of the simulation is done explicit with the solver ls-dyna_smp_s_r910_x64. Evaluation of the computation is done on the basis of the resulting strain distribution. Hence, the maximum drawing depth is determined, which should lie in between the two identified forming limit curves. This case is present at a drawing depth of 21.8 mm, see Figure 4.

Additionally to the formability, obtained in hydraulic bulge tests, uniaxial tensile tests are evaluated, regarding the formability at a negative minor strain. Reason for the differences in the formability plots on the left hand side, is the Lankford coefficient that is frD = 0.77 in rolling direction and frTD = 0.93 in transversal direction. A Lankford coefficient of r = 1.0 defines an isotropic material flow in all directions and therefore has a higher formability (TD) than a lower Lankford coefficient (RD). Indeed this influence is only applicable oft uniaxial tensile test and is not suitable for the plane strain area.
There, the grain structure after the rolling process is the explanation. In transversal direction, there are more grain boundaries and therefore there is a higher flow restriction and reduced formability than in rolling direction.

The numerical mapped deep drawing process leads to a failed part, when considering the conventional approach for the forming limit evaluation as given in the standard. Taking into account the significant direction dependency of the material DP600 and using the material properties in orthogonal direction, the process leads to a good part.

### 4.2 Experimental validation

In the following, the direction dependency, characterized in the hydraulic bulge tests are validated by deep drawing of square cups with the parameter setup of the numerical process, 190 kN blank holder force, a drawing depth of 21.8 mm and a well lubricated blank, as seen in Figure 4 for the simulation. The resulting cups are depicted in Figure 5 in comparison to the determined formability with the particular forming limit curve. Results reveal the good accordance of the numerical and experimental cups. In transversal direction, the simulation prognoses a risk of cracks but no certain cracking. The same can be observed for the deep drawn cup, which shows no crack and no severe thinning that would be visible through local necking. In contrast to this, for the cup in RD cracking is predicted at the beginning of the punch curvature at the short side of the square. This is also the region, where cracking starts in the experiment, see red mark on Figure 5 on the right. The experiments show, that considering the significant direction dependent material behaviour can increase the maximum deformation i.e. the drawing depth of a part. Considering this in process design, the forming limits can be improved.

The predicted minimum formability can be seen as well in the formed parts. A blank that is applied in the press in transversal direction will crack, while a blank in rolling direction is formable. Explanation is the rolling process of the blank which leads to an increased number of grain boundaries in transversal direction and therefore to a reduced formability. This effect is significant for materials with $r$-values under 1.0 because material flow in thickness direction raises with reduced $r$-values. In contrast to this, materials with $r$-values above 1.0 do not show that significant change in formability which is 50 % in the case of DP600. For the mild steel DC06 with $r_{RD} = 2.20$ and $r_{TD} = 2.64$, the maximum major strain characterized in elliptic hydraulic bulge tests is 0.39 in RD and 0.41 in TD.
5 Summary and outlook
The prediction of the material specific forming limit especially in the near plane strain area is essential for a numerical process design. Material characterization for the dual-phase steel DP600 in an elliptic hydraulic bulge test reveals a significant difference in the flow curve regarding the maximum strain of about 50%. Therefore, this testing setup is used to additionally obtain strain data for defining a strain based fracture criterion. The defined forming limits are verified with conventional Nakajima tests, to guarantee the accuracy. For the plane strain area, the Nakajima and the elliptic bulge tests prove the applicability. Due to the anisotropic formability DP600 should be deep drawn in optimized position, to utilize the entire potential of the material. Therefore, the process has been numerically mapped and validated with experiments. As predicted, the cup in transversal direction could be deep drawn, while the cup in rolling direction cracked during the deep drawing process. This effect can be relied to the Lankford coefficients of the DP600.

Results prove that the presented hydraulic bulge testing setup is suitable to obtain data for the modelling of both, the plastic material behaviour as well as strain data for the evaluation of the forming limits. Due to the significant anisotropic formability, the forming limits can be improved by identification of the ideal position of the blank according to the rolling direction. Further investigation should be done with more different geometries of the elliptic die to obtain more stress based material properties, for example for the implementation of the Veger yield criterion and parallel for a more precise characterisation of the forming limits. Also, other high strength materials with a Lankford coefficient below 1 should be analysed.

6 References
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