Evaluation of testing methods for the characterization of material properties under plane strain

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Abstract. With the first numerically calculated forming simulations of a complex component by Hora in 1987, a renewed need emerged for a large number of stress-based material parameters for the yield locus modelling. Material characterization and modelling under plane strain is an important step towards an improved mapping accuracy in numerical calculated sheet metal forming processes. There are numerous of different testing methods, which can be used for this purpose. It is crucial to choose the right experiment depending on which material properties or characteristic values are needed. The aim of this investigation is to analyze the suitability of the currently mostly used testing methods that induce a plane strain in the material, the notched tensile test, the biaxial tensile test and the hydraulic bulge test with an elliptical die. For this purpose, the stress-based material properties of DC06 in all three tests are determined and compared. Subsequently, recommendations for material characterization are derived depending on the application.

1. Introduction

Nowadays, efficient and versatile manufacturing processes are based on a precise numerical design. Thus, material models with a high mapping accuracy are needed. Due to the improved possibilities in material characterization, models with an increasing number of degrees of freedom can be identified. The use of optical measuring systems has further increased the possibilities for determining characteristic values. Since the first numerical calculation of a sheet metal forming process by Hora in 1987 [1], there has been a further demand for improved mathematical models to describe the plastic material behavior as accurately as possible. These mathematical descriptions of the observed material behavior enabled finite element (FE) analyses of the forming processes and can significantly reduce development time and costs in the tooling design. A mathematical formulation that has the degree of freedom to correctly represent the plasticity of deep drawing steel grades requires significantly more input parameters than available in conventional models. These parameters are provided by experiments in order to be able to characterize the material behavior under different types of loading in laboratory tests. Thus, the experimental effort goes hand in hand with a better mapping accuracy and is contrary to a time- and cost-efficient process design. A stronger interaction between experiments and modelling offers the possibility of an increase in efficiency in numerically calculated sheet metal forming processes.

Due to the minimal forming limit under plane strain and a relatively high rate of failure of about 80% in the plane strain area [2] there is currently a focus on the material characterization and modelling under plane strain. Among others, three testing methodologies are mostly used, when it comes to the material characterization under plane strain loading, the notched tensile test, the biaxial tensile test or the hydraulic bulge test with an elliptical die, that induces a near plane strain load in the material. All
three test have their special limitations and advantages. In the notched tensile test, only the first principle stress can be characterized. Wagoner [WAG80] proposed an analytical formulation with reference to the Lankford coefficient for a calculation of the second principle stress component. However, for accurate modelling of yield locus curves, the first and second principal stress components are required. This could be overcome by Kuwabara [4] with his biaxial tensile test. The limitation in these investigations was the maximum true strain of 0.09 for an IF steel grade. Investigations of Hippke et al. [5] used the biaxial tensile test for testing of many sampling points in the first quadrant of the yield locus. In this case, the maximum elongations were in the true strain range between 0.01 and 0.02, depending on the load case. Another test setup that is suitable for material characterization in plane strain is the hydraulic bulge test with an elliptical die. As valid for all die geometries in the bulge test, the initial yield stress cannot be calculated with sufficient accuracy due to the evaluation methodology. Possible applications of the material properties under plane strain are the identification of the yield criterion of Veger [6] or an implementation in other yield criteria, for example Yld2000-2d via variation of the yield locus exponent m [7] with the additional experimental data [8]. Hippke et al. [5] proved the better mapping accuracy of the optimized yield locus model through a comparison of the prognosed stress values in the first quadrant to those characterized in biaxial tensile tests.

It can be concluded, that there is a need for experimental parameters for the numerical simulation but there is a lack of comprehensive understanding of which experiment can or should be used for which material information due to the different limitations of each test setup. In this investigation the suitability of the three mentioned testing methods are analyzed. Therefore, a material characterization is done with the notched tensile test, the biaxial tensile test and the hydraulic bulge test with an elliptical die. Further, the stress-based material properties of DC06 in all three tests are analyzed and compared. Subsequently, recommendations for material characterization are derived depending on the application.

2. Methodology and testing setups

For a comprehensive understanding of the material behavior under plane strain, tests with the different testing setups are performed. The used material should have a load path dependent anisotropic hardening. This is an important attribute because the load paths are slightly different in the elliptic hydraulic bulge test and in the notched tensile test. In the notched tensile test, there is no second principle strain component while in the bulge test there is a ratio of 1:5 for the second to the first principle strain [8]. For this reason these two strain paths are adapted in the biaxial tensile test for this investigation by a special specimen design and different loading conditions. As a result, there are four different yield curves out of the three tests and the two load paths which are further qualitatively and quantitatively analyzed with respect to the maximum elongation and the resulting flow stress values. Based on these findings, recommendations for the material characterization under plane strain are derived.

Material

The used material is the DC06 with a sheet thickness of 1.0 mm. Due to its good formability and the associated excellent suitability for deep drawing, the material is also referred to as deep drawing steel. It is characterized by a low initial yield stress, a distinct work hardening and a high ductility. However, the anisotropic hardening behavior [9] is a challenge for this steel grade, which makes precise numerical mapping difficult.

Notched tensile test

The notched tensile tests are performed on the universal testing machine Z100 (Zwick, Germany). The strain is measured with a 3D DIC device ARAMIS (GOM, Germany). The specimen has a width of 60 mm with notches that result in a transverse section reduction to 30 mm. In the notch there is a parallel length of 2 mm and two radii of 2 mm. Due to the localization of plastic strain in the notch, a constant testing velocity of 3.0 mm/min for the steel material is used. The measuring frequency for force and strain is 2 Hz. Specimens are tested in the rolling direction (RD). The determination of yield curves under plane strain is based on the methodology of Flores et al. [10].
Elliptic hydraulic bulge test (HBT)

The hydraulic bulge tests with an elliptical die are performed with the tool presented in [8]. The tool is adapted in a hydraulic press Hydrap HDPZb630 (Hydrap, Germany). Again the strain measurement is done by 3D DIC. The strain velocity of 4.0 %/s is online controlled by the DIC system through a regulation of the volumetric flow of the hydraulic fluid. Thus, a constant deformation rate can be guaranteed within the whole test. Analogous to the notched tensile test, the material characterization is done in rolling direction.

Biaxial tensile test

The biaxial tensile tests are performed with the testing machine published by Merklein and Biasutti [11]. The test rig is based on a base plate that can be moved in the z-axis, with four clamping jaws mounted on it, which are fixed to a lower immovable table plate by means of a joint kinematics. The lifting movement of the base plate generates a tensile force on all four arms due to the fixation of the arms. By setting different angles in the joint kinematics, a different increase in strain in each tensile direction can be generated. This allows strain paths to be realized under equi-biaxial or near plane strain. The test forces occurring during deformation are characterized using four load cells, one in each arm. The strain is recorded with a 3D DIC system. Different strain paths can be realized not only by the kinematics of the test rig. Numerous publications on specimen geometries, summarized for example by Bruschi et al. [12], show the relevance of the specimen shape for material characterization in biaxial tensile testing. The investigations are carried out on the basis of two strain path based target variables. On the one hand, the strain path obtained in the elliptical hydraulic bulge tests is reproduced via different loading angels of the joints as mentioned above. On the other hand the strain path in notched tensile tests has to be replicated. Thus, the specimen shape and the test rig are adapted in such a way that an ideal plane strain state results.

3. Results and discussion

An analysis of the plastic material behavior is carried out in a first step by experimental data provided from notched tensile tests and hydraulic bulge tests with an elliptical die. The stress calculation in the notched tensile test is done according to Flores et al. [10] with a maximum allowable perpendicular strain of 2.0 %. The parameter $\alpha$, for the homogeneous length, was set to $\alpha = 0.98$. The yield stress calculation in the hydraulic bulge tests is done according to [8]. The resulting flow curves of both tests and the corresponding strain paths are shown in Fig. 1.

![Figure 1](image_url)  
**Figure 1.** a) Flow curves out of notched tensile tests and elliptic hydraulic bulge tests of the materials DC06 and b) resulting strain paths

A qualitative comparison of the flow curves shows a very good comparability of the curves between the elliptical hydraulic bulge test and the notched tensile test up to a first principle strain of 0.05. In the beginning of yielding, however, a comparison is not possible, since the stress evaluation in the hydraulic...
bulge test is not possible in this strain level and starts at approximately 0.01 true strain. Above 0.05 true strain, the strain hardening behavior in the notched tensile test is lower than in the hydraulic bulge test. The reason for this is, on the one hand, the localization of the strain and the associated locally different sheet thickness along the forming zone due to the tensile stress superposition at the specimen edge [10]. For clarification, optically measured strain fields at different pre-strains are shown in Fig. 2. While at 0.05 true strain a relatively homogeneous straining is observable in the whole forming zone, except a small region at the radii. In contrast to this, significant inhomogeneities can be identified above 0.05 true strain for both major and minor strain with a clearly tendency to tensile loading conditions with a negative minor strain and positive major strain. In addition, the strain components are evaluated on the sheet plane as a basis for the thickness calculation along a measuring field in the center of the specimen. In this forming zone, locally different strain values in this area are averaged and leads to a mean strain value that is too low [13]. The third influencing factor is the anisotropic work hardening of this material, that leads to a different yield stress under tensile loading and under plane strain, whereby the biaxial strain of this material class leads to a higher stress values [9]. For this reason, in combination with an insufficiently precise measurement of the local plate thickness, the yield stress determined in the notched tensile test is output with a value that is too low.

![Figure 2. Distribution of major and minor strain in the notched tensile test at defined stages of deformation for DC06](image)

Both tests for the characterization of the plane strain lead to a similar result at low degrees of deformation. Limitations in the determination of the onset of yielding in the HBT and the characterization of strain hardening in the notched tensile test make it necessary to conduct a further test in order to be able to characterize and analyze the plastic material behavior holistically. On the basis of the different strain paths of notched tensile test and elliptical hydraulic bulge test, a testing procedure is therefore developed which can characterize the onset of yielding for both stress components at ideal plane strain as well as at near plane strain. The analysis for both load cases is necessary because the investigated material exhibits a stress-state-dependent strain hardening [9]. Therefore, it is essential to analyze the difference of the flow curves for the different load paths. For this reason, specimen geometries and loading conditions are being developed which correspond to the tests and can be
reproduced in one test rig. With the two resulting strain paths in Fig. 1, the loading conditions and specimen geometries in the biaxial tensile test are improved. The resulting geometries and loading conditions are shown in Fig. 3.

To achieve the objective of a strain path with ideal plane strain (variant on the left), concave contours of slits in the specimen in the tensile loading direction are investigated. The shape of the concave slot structure and load distribution is adapted so that quasi-ideal plane strain ($\varepsilon_2 = 0$) dominates in the middle region of the specimen. For this purpose, elongation of the specimen in the transverse direction is prevented by a solid fixing of the tensile arms. Examination of the remaining width in the transverse direction results in a width in the center of the specimen of 2 mm. A higher width leads to a major strain below 3 %. The slits in the arms in the tensile direction are applied to homogenize the strain in the loading direction [11]. A strain path can be achieved with the specimen shape shown in Fig. 3 (variant on the right), that is comparable to elliptical hydraulic bulge tests. Here, the main loading direction is along the slitted arms. The minor strain is in the direction of the unslitted arms. In this direction, a lower testing velocity $v_2 < v_1$ is applied. The resulting strain paths based on both geometries and loading conditions are shown in Fig. 3 on the right.

![Diagram](image)

**Figure 3.** Resulting specimen geometries and load paths for the biaxial tensile test

Testing of the biaxial tensile test specimen, which corresponds to the strain path in the notched tensile test, leads to a vertically load path with no significant minor strain (black line). A limiting factor for this geometry is the maximum achievable strain in the specimen center of 3 %. In the second variant, shown in grey, a major strain of 6 % is reachable before failure of the tensile arms. The early failure in the arms can be explained by the reduced cross section in this area due to the slits. A milling of the sheet metal in the area of the specimen center which is relevant for material characterization to a lower sheet thickness, would on the one hand increase the achievable maximum strain. On the other hand due to the mechanical processing, an influence on the material properties cannot be completely excluded.

For the biaxial tensile test setup with ideal plane strain, the curves of the first and second principal stress are shown in Fig. 4. The stress curves resulting from biaxial tensile tests correlate with the stress curves from elliptical hydraulic bulge tests. The mean difference of 4.8 MPa between the two tests is within the standard deviation of the respective tests. A stagnating course of the second principal stress at the beginning of plastic deformation is visible. This can be explained by the existing preload, which is necessary for fixing the specimen in the tool. Also the flow curves at near plane strain of the biaxial tensile tests in Fig. 5 are in good agreement with the curves from elliptical hydraulic bulge tests. In this configuration, the mean difference between the principal stress curves is 2.8 MPa. Due to this significant correlation, this testing setup is suitable for determining the onset of plastic deformation under plane strain. The resulting yield stresses for both principal stresses is $\sigma_1 = 199.4$ MPa and $\sigma_2 = 104.7$ MPa with a maximum standard deviation of 3.0 MPa.
4. Discussion

A comparison of all three curves at the onset of plastic deformation shows a very good agreement between the stress curves up to a plastic strain of 0.05, see Fig. 6. Based on this, the notched tensile test is also suitable for characterizing the first principal stress component under plane strain. For notched tensile tests, the onset of yielding is 199.9 MPa. In comparison, the biaxial tensile specimen yields at 201.1 MPa. As a limitation, it must be taken into account that the second principal stress component, which is required for yield locus modeling, cannot be determined. Based on the analysis of the first principal stress, both test methods - biaxial tensile test and elliptical hydraulic bulge test - are suitable to perform a material characterization under plane strain, since the deviation from the established procedure with notch tensile tests [10] does not show significant differences in the yield stress. The use of these test methods for material characterization in the plane strain condition is thus possible. Based on the results, the individual tests are evaluated on the basis of the characteristic values that can be determined. Furthermore, the flexibility and suitability for material modeling of the three tests are categorized in Table 1. This means that, depending on the application or the required material characteristic value, a different test method is appropriate.

In both the biaxial tensile test and the elliptical hydraulic bulge test, the characterization of both principal stress components is possible. In the bulge test, the material hardening can be characterized up to failure (ε large). In the biaxial tensile test the characterization of the onset of flow is possible (ε small). The notched tensile test is basically suitable for characterizing the first principal stress up to an
equivalent plastic strain of 0.08 for DC06. This allows initial conclusions to be drawn about the work hardening behavior of the used material. Furthermore, the notched tensile test requires a complex preparation of the measured values, since the material thinning is unevenly due to an inhomogeneous stress distribution in the notch [10]. A positive aspect of the notched tensile test, however, is that an ideally plane strain state can be achieved for the material characterization. This is also possible for the biaxial tensile test. In this test, the flexibility for strain path variations with a positive or negative second principle strain can be easily adjusted. In the elliptical hydraulic bulge test, only a near plane strain state with slightly positive second principle strain can be adjusted. Due to the test concept, the ideal plane strain state cannot be achieved. In order to generate a further support point in the yield locus curve, the bulge test is well suited due to the determination of first and second principal stress, since the determined point can be displayed directly in the two-dimensional stress space and therefore be used for an optimization of the yield locus geometry. This is also possible for the biaxial tensile test. The notched tensile test does not offer this possibility. It is only possible to define a boundary for the first principal stress component, which must not exceed the yield locus curve at the point of the largest first principal stress. This can be represented as a vertical line in the diagram of the yield locus curve in the system of principal stresses. A direct application for a yield locus curve modeling results from the first principal stress component only to a limited extent in that the yield locus curve must tangentially touch the determined yield stress in notched tensile tests. The value of the second principal stress results only from the contour of the yield surface and does not necessarily have to correspond to the real material behavior. This test is therefore not suitable for the model parameter identification of the stress space.

Table 1. Evaluation of the test methods for plane strain with regard to determinable parameters, flexibility in strain path design and suitability for yield locus modeling

| Testing setup           | Determinable parameters | Flexibility in strain path changes | Suitability for yield locus modelling |
|-------------------------|-------------------------|------------------------------------|--------------------------------------|
| Notched tensile test    | $\sigma_1$, $\varepsilon$ medium | -                                  | -                                    |
| Elliptic hydraulic bulge test | $\sigma_1$, $\sigma_2$, $\varepsilon$ high | -                                  | +                                    |
| Biaxial tensile test   | $\sigma_1$, $\sigma_2$, $\varepsilon$ low | ++                                 | +                                    |

Figure 6. Comparison of the flow curves characterized in all three tests under plane stain loading for DC06.
5. Conclusion

A precise determination of the material behavior under plane strain conditions is important to obtain correct results in the numerical process design of sheet metal forming processes. In 1987, at the time of the first numerical analysis of complex components, the demand for better material data was already formulated by Prof. Hora. This demand could only be met later with improved measurement capabilities, especially DIC. Thus, more than 30 years ago, Prof. Hora's demands for better material data influenced the rethinking of material characterization, especially since the end of the 1990s, and the adoption of new methods with DIC. Based on this history, tests and testing setups for improved material characterization are available today in order to meet the requirements of that time. In this context, too, are the results of this investigation and the following conclusions can be drawn:

- For a complete understanding of the plane strain material behavior it is necessary to conduct two different tests
- Depending on the necessary parameters, it is possible to perform the notched tensile test and the elliptic hydraulic bulge test or the biaxial tensile test and the hydraulic bulge test
- Also for materials with anisotropic hardening the slightly different load paths lead to comparable flow curves and therefore can equally be used for the material characterization

Further investigations should focus the transferability of the findings to other material classes with and without a stress state dependent hardening behavior.

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