Potentials for material card validation using an innovative tool

M Eder¹*, M Gruber¹, N Manopulo² and W Volk¹

¹ Chair of Metal Forming and Casting, Technical University of Munich, Germany
² AutoForm Development GmbH, Zurich, Switzerland

E-mail: matthias.eder@utg.de

Abstract. For the numerical description of the material behavior of sheet metals, there is a large diversity of models. These models vary strongly in terms of complexity and calibration effort. Before using a material model for numerical analyses, it is essential to validate it. The paper presents an innovative tool that allows generating a well-founded database for a comprehensive validation of the yield locus description with few and simple tests: the MUC-Test (Material Under Control). The special geometry of the punch and die generates complex strain distributions in sheet metal samples during forming. The experiment covers the strain range between uniaxial and equibiaxial tension. The contribution shows the potential of this innovative tool by using the test results of three different material classes. Using numerical analyses, sensitivities of different material model parameters were investigated. Thereby, the focus lies on the curvature of the yield locus in the area between uniaxial and equibiaxial stress state.

1. Material models in sheet metal forming
In the last decades, numerical analysis has become an indispensable tool for virtual product development, especially in the automotive and aviation industries. Numerical analyses are also increasingly used for the development and optimization of forming processes. In sheet metal forming, finite element programs (FEM) are used to predict the geometries and properties of components and optimize them by varying the process parameters and the tool shape [1]. In order to describe the behavior of the material in the numerical investigations, material models are implemented in the FEM. Accordingly, the results of the numerical analyses depend directly on the input parameters of these models. Depending on how the material behaves under load and how complex the material is to be modelled, more or less experimental investigations are required to determine required parameters. In particular, different models may lead to large differences in the plastic flow behavior. For example, for the Hill1948 yield criterion [2] three parameters have to be determined (the Lankford coefficients in three angles regarding the rolling direction), whereas for a Yld2000-2D [3] or BBC2005 [4], eight parameters are required. [5]

Often, the experiments can only be tested with special equipment and are very costly, so it is important to model the material behavior as simple as possible but as complex as necessary. To evaluate this requirement, a validation of the models is essential [6]. Therefore, a new method was introduced by Eder et al. [7]: the MUC-Test (Material Under Control).

2. Methods for the validation of material models
In the field of forming technology, the validation of models is usually based on the strains, as they can be optically measured. By comparing experiments and numerical analyses, conclusions can be drawn directly on the quality of the material model. Essential for the comparison is the continuous recording
of the decisive data in the experiment, as the hardening behavior is usually path-dependent. DIC (Digital Image Correlation) measuring systems are used for the strain measurement, so potential validation experiments for forming technology should be optically accessible.

The experiments for determining the material parameters can be divided into homogeneous and heterogeneous experiments. The homogeneous experiments are for example the tensile test, the bulge or Nakajima test. Each of these tests leads to a quasi-homogeneous strain field, which makes it possible to validate only a limited number of model parameters. This in turn means that a large number of tests are required to comprehensively validate the material. Thus, a validation test should be simple and performed with a small number of tests, to ensure efficiency. Therefore, heterogeneous tests are recommended for validation, where a wide spread strain distribution leads to many information that can be used for a validation with only a small number of tests. One way of obtaining such a non-homogeneous deformation is by altering the geometry of the specimen for uniaxial testing. This has the advantage that it is a frictionless validation method. The so-called Yoshida buckling test is a well-known example for the modification of a tensile test. Compressive stresses in the center of the specimen cause thickening and thus wrinkles and more complex strain distributions can occur [8]. Aquino et al. take advantage of this principle and use it for validation strategies of material models in their butterfly test. Thus, complex distributions can be generated in the strain area between ideal deep drawing and uniaxial strains. Several strain states can be mapped within one test and compared with the numerical tests. This comparison can be used to evaluate the material model or determine parameters inversely [9]. The plane strain and the biaxial strain areas are particularly interesting for material validation. With a tensile test approach, however, it is difficult to generate strains in this area.

Another heterogeneous experiment for the evaluation of material models is the cross-die test [10]. The main advantages of this test are that the test conditions are comparable to industrial conditions and that with the cross-shaped geometry also strains in the plane strain and biaxial section can be created. This allows the material model to be evaluated over a wide range of stress and strain conditions. The big disadvantage of the experiment is the friction dominance. Since the material flows into the tool during the forming process, frictional effects must be taken into account and have to be evaluated together with the material model. Furthermore, when using the cross-die tool it is not possible to measure the strains in-line, as the tool consists of a punch and die and is closed while the forming process. Only the initial and final state can be compared between the experiment and the numerical analysis.

The state of the art shows that first investigations on the subject of material validation already exist. However, it also shows that the various approaches still have individual disadvantages, either in the complexity of the strains or in the friction dominance. Our motivation for the MUC-Test was therefore to invent a validation test that fulfils the following characteristics:

- Simple test execution
- Small number of tests
- Continuous data acquisition over time
- Low frictional influence
- Complex strain distribution

3. Innovative tool for material model validation: MUC-Test

In order to guarantee the simple test conduction, the Nakajima standard ISO 12004-2 was followed in the development of the novel tool for material model validation [11]. Therefore, the geometry, the mounting points, and the tolerances are designed for a sheet metal testing machine, BUP1000 from ZwickRoell, which is used in the Nakajima experiment. First numerical analyses have shown that it is possible to represent the strain range between uniaxial and equibiaxial strain with just three rectangular specimen geometries. Thus, the requirement for a small number of simple tests that are necessary for a
comprehensive validation is fulfilled. With the not rotational-symmetric shape of the tool, shown in Figure 1, it is possible to create the complex strain distribution. The low frictional influence is achieved by the drawbead, which blocks a material flow. As the die of the tool is open to the top, it is also possible to measure the strains by DIC continuously. Accordingly, the MUC-Test meets the requirements and is a serious option for material validation.

4. MUC-Test for different materials

4.1. Test conditions
The presented MUC-tool is used on a BUP1000 from ZwickRoell. The blankholder force was set to 400 kN for all tests, the punch velocity to 1.0 mm/s. The lubrication system consisted of two layers of deep drawing foil and lubrication paste. For each material, sample geometries with widths of 70 mm, 110 mm and 230 mm were investigated, see Figure 2. For the strain measurement using ARAMIS from GOM, the samples were sprayed with a speckle pattern. In all performed tests, the rolling direction is along the x-direction of the specimen, see Figure 2. Three different materials were investigated for this publication: the microalloyed steel HC340LA (CR300LA) with a sheet thickness of 1.0 mm, the interstitial free steel HC260Y (CR240IF) with a sheet thickness of 1.0 mm and the aluminum alloy AA5083 with a sheet thickness of 1.8 mm. For each experiment, at least three repetitions were conducted.

4.2. Strain distributions for different materials
To show the results of the experiments, the strain distributions of the respective experiments without repetitions are shown in Figure 3. The punch strokes for the diagrams were chosen so that the maximum major strain for the materials HC340LA and HC260Y is about 0.3 and for AA5083 about 0.2. These states were selected because significant forming has already taken place, but no failure due to localized necking or fracture has yet occurred.

The strain distributions in Figure 3 show varying characteristics for the different materials. HC340LA shows a V-shape for the 70 mm sample, whereas a third branch is formed for the material

![Figure 1. Tool for the MUC-Test.](image1)

![Figure 2. Specimen geometries.](image2)

![Figure 3. Exemplary strain distributions for the specimen geometries 70 mm, 110 mm and 230 mm of the materials HC340LA (left), HC260Y (center) and AA5083 (right).](image3)
HC260Y, which results in a W-shaped characteristic. For the aluminum AA5083 a fundamentally different characteristic is formed, which is in the range of plane strain. In the case of the 110 mm specimen, HC340LA primarily forms only one branch in the strain distribution in the plane strain range; another branch in the direction of uniaxial strain is roughly visible. For the interstitial-free HC260Y, in contrast, both branches of the strain distribution appear at similar levels. For the aluminum, the strain distribution characteristic of the 110 mm specimen is comparable to the distribution of the 70 mm specimen with a shift towards more positive minor strains. The 230 mm specimens are clamped over the entire die by the locking bead. Therefore this is the specimen with the most tightly defined geometric boundary conditions, which leads to differences in the strain distributions that are minor compared to the other specimen.

This shows that it is possible to reveal varying material behavior using the MUC-Test. This sensitivity is essential for an effective validation of material models. Furthermore, it can be seen that the strain distributions, especially for steel materials, cover a wide strain range, which makes a comprehensive validation of material models possible.

4.3. Investigation of reproducibility

For all the materials, the MUC-Test was performed with three repetitions for each sample geometry, to investigate the reproducibility of the experiment. Figure 4 shows the strain distributions for all sample geometries of HC340LA with three repetitions each.
Sections along two punch directions allow a more precise study of the reproducibility. Figure 5 shows the position of the two sections exemplarily on a 230 mm sample. They lie longitudinal and transverse along the punch.

Figure 6 shows the strain ratio (minor strain divided by major strain) along the two sections for the different sample geometries. For all sample geometries, there is only a slight scattering of the measured strains for different test repetitions. This shows that it is possible to obtain reproducible results using the MUC-Test. This is an essential requirement for the test in order to generate a well-founded data basis for a material card validation.

5. Numerical analyses of the MUC-Test
The following section shows numerical analyses of the MUC-Test exemplarily for the material HC340LA. The sensitivities of a selection of material parameters on the strain distributions are examined. Special focus is laid on the curvature of the yield locus description between uniaxial and equibiaxial stresses. The software used for the numerical analyses was AutoForm R8. The sensitivities of the investigated material parameters were examined with respect to a reference material model.

The model BBC2005 was used for the description of the yield locus [12]. The yield curves and Lankford coefficients (\( r \)-values) in three directions with respect to the rolling direction were determined by uniaxial tensile tests according to the standard ISO 6892 [13]. Further, the uniaxial stress ratios were derived from these tests. The strain rate sensitivity was investigated in uniaxial tensile tests at different strain rates. For the extrapolation of the uniaxial flow curve and for the determination of the biaxial stress ratio, the hydraulic bulge test according to ISO 16808 [14] was used. The biaxial anisotropy coefficient (\( r_{90} \)-value) was calculated on the basis of the yield locus description Hill1948 [12]. For a more realistic representation, it would be better to use an experimentally determined \( r_{90} \)-value [3]. In this study, however, the focus is rather on a relative sensitivity analysis than on the best possible representation. The parameters for the used material HC340LA are summarized in Table 1. The exponent of the BBC2005 model was set to \( M = 6 \) for the reference material model. The friction between the sheet metal and the blank holder respectively the die is modelled using a friction coefficient of 0.08. The friction between the blank and the punch is significantly lower due to the used lubrication system. The remaining friction was modelled by a friction coefficient of 0.015. The meshing was done with an edge length of 1.45 mm, according to the reference strain length used in the DIC system. An automatic mesh refinement was not applied. Based on this reference material model, the sensitivity of various parameters to the resulting strain distribution is qualitatively investigated below.

| Table 1. Mechanical properties of the used material HC340LA. |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| \( \sigma_0/\sigma_y \) | \( \sigma_{45}/\sigma_y \) | \( \sigma_90/\sigma_y \) | \( r_0 \) | \( r_{45} \) | \( r_{90} \) | \( r_9 \) (Hill1948) |
| 1 | 0.992 | 1.030 | 0.972 | 0.668 | 1.062 | 0.904 | 0.739 |

5.1. Influence of thickness stress
Usually the material behavior of metal sheets is modeled by means of the membrane assumption of plane stress. In the case of high contact pressures due to one-sided tool contact, significant stresses in the direction of the sheet thickness can occur. AutoForm R8 offers the possibility to consider this effect with the Thickness Stress option. Figure 7 shows the effect of considering thickness stresses on the strain distributions for the three different test geometries.

Figure 7 shows that consideration of the stress in the sheet thickness direction has a significant influence on the strain distribution for all three specimen. The deviations between experiment and numerical analysis are significantly smaller when taking the thickness stresses into account. Notwithstanding, there are still deviations between experiment and simulation. Since other parameters also influence the strain distribution and the usage of the through thickness stresses better reflects reality, all further numerical analyses are executed using this function.
5.2. Influence of curvature (BBC-M-Value)

An essential parameter that defines the curvature of the BBC2005 yield locus is the exponent \( M \). This parameter is usually not directly determined experimentally. Knowledge of the sensitivity of the \( M \)-value is of major interest for the MUC-Test. A value of \( M = 6 \) has been chosen as a reference value, which can be found as a standard value for steel materials in publications [12]. Starting from a value of \( M = 6 \), as shown in Figure 7, it is varied to \( M = 4.5 \) and \( M = 8 \). Figure 8 shows the influence of the \( M \)-value on the strain distributions for the three specimen geometries investigated.

It can be seen that the \( M \)-value, especially for the 70 mm and 110 mm specimen, has a significant influence on the strain distribution. It is also evident that the \( M \)-value has an influence on the failure behavior. For \( M = 8 \) the strain distributions of the 70 mm and 110 mm specimens are already instable. Furthermore, the comparison with Figure 7 shows that \( M = 4.5 \) represents the strain distributions better than a standard value of \( M = 6 \), so a value of \( M = 4.5 \) is used for all further numerical analyses. The influence on the 230 mm specimen is comparatively weaker, since the curvature in the equibiaxial stress range is mainly controlled by the biaxial anisotropy coefficient \( r_b \).

5.3. Influence of biaxial anisotropy coefficient

The reference value of \( r_b = 0.739 \) was calculated based on Hill1948. Based on this, \( r_b \) values of 0.6 and 0.96, the maximum possible value for the reference material parameters, were analyzed numerically. The influence of a variation of the biaxial anisotropy coefficient \( r_b \) on the strain distributions in the MUC-Test is shown in Figure 9.
As expected, the $r_b$-value has only a minor influence on the strain distribution of the 70 mm specimen. In the corresponding uniaxial stress range, the curvature of the yield locus is mainly determined by the uniaxial anisotropy coefficient $r_0$ as well as by the $M$-value, which is why the $r_b$-value has only a minor influence on the result. The $r_b$-value shows the greatest influence on the 230 mm sample. Here it can be seen that an $r_b$-value of 0.96 reproduces the strain characteristic in the biaxial range better than the reference value of 0.739. However, for a final qualification of the $r_b$-value, the influence on sample geometries with a different rolling direction must also be investigated, since the $r_b$-value also has a corresponding influence on these. In addition, the influence on the 110 mm sample must also be taken into account.

5.4. Influence of Lankford coefficient
Finally, the influence of the Lankford coefficient $r_0$ on the strain distributions is investigated. Even if this parameter can be determined in the standard tensile test, there is still a measurement uncertainty. To investigate the sensitivity of the $r_0$-value, numerical analyses with $r_0 = 0.5$ and $r_0 = 0.85$ were performed compared to the reference value of $r_0 = 0.668$, see Figure 10.

A significant influence of the $r_0$-value on the strain distribution of the 70 mm specimen is evident. With increasing $r_0$-value, the strain distribution shifts to minor strains that are more negative. This corresponds to the expectation that as the $r_0$-value increases, the plastic material flow emerges more from the width of the specimen, which leads to more negative minor strains. The influence on the 110 mm sample is moderate; the influence on the 230 mm sample is, as expected, small.

Figure 9. Influence of the biaxial anisotropy coefficient $r_b$ on the strain distribution of the 70 mm (left), 110 mm (center) and 230 mm (right) specimen.

Figure 10. Influence of uniaxial anisotropy coefficient $r_0$ on the strain distribution of the 70 mm (left), 110 mm (center) and 230 mm (right) specimen.
6. Summary and outlook
In the present work, a new tool for the validation of material models for sheet metal materials was presented: the MUC-Test (Material Under Control). This tool allows the generation of a comprehensive database for an effective and efficient validation. The basis for this suitability is the special geometry of the tool, which generates wide spread strain distributions. By using a locking bead, the test is not friction dominated. Another major advantage of the MUC-Test is the small number of experiments required as well as the simple test procedure.

Experiments were carried out with materials from three different material classes. The resulting strain distributions show significant differences in their characteristics. This leads to the conclusion that the MUC-Test is suitable for different material classes and that it is possible to detect differences in material behavior. Also, the results show that the MUC-Test achieves a good repeatability of the results.

Furthermore, numerical sensitivities of different material model parameters were investigated. This investigation has shown that the chosen material model significantly influences the results of the numerical analysis. Additionally, the tendencies of material parameters, which mainly influence the curvature of the yield locus, were shown. The clear correlation between material model and result of the numerical analysis is essential to prove the suitability of the MUC-Test for material card validation.

In a further step, it is necessary to investigate other material classes in terms of their suitability for the MUC-Test. In future work, the time continuous data can be used to evaluate the hardening behavior of material models. It can also be aimed to improve existing material models with the help of the generated data. A further approach for the use of the MUC-Test is the performance of a material benchmark to identify and evaluate differences between materials or batches.

Summarized, it can be concluded that the presented MUC-Test, in addition to the potentials for material card validation, offers a multitude of different applications in the field of sheet metal forming.

Acknowledgement
The authors would like to thank the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG) for the financial support under the grant numbers VO 1487/59 and VO 1487/32.

References
[1] Tekkaya A E 2000 J. Mater. Process. Technol. 103 14.
[2] Hill R 1948 Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences 193 281.
[3] Barlat F, Brem J C, Yoon J W, Chung K, Dick R E, Lege D J, Pourboghrat F, Choi S-H and Chu E 2003 Int. J. Plast. 19 1297.
[4] Banabic D 2005 Int. J. Plast. 21 493.
[5] Bruschi S, Altan T, Banabic D, Bariani P F, Brosius A, Cao J, Ghiotti A, Khraisheh M, Merklein M and Tekkaya A E 2014 CIRP Ann. 63 727.
[6] Volk W, Groche P, Brosius A, Ghiotti A, Kinsey B L, Liewald M, Madej L, Min J and Yanagimoto J 2019 CIRP Ann. 68 775.
[7] Eder M, Gruber M and Volk W 2019 Innovative Tool for Material Model Assessment and Improvement Proceedings of the 12th Forming Technology Forum (FTF).
[8] Cao J, Cheng S H, Wang H P and Wang C T 2007 CIRP Ann. 56 253.
[9] Aquino J, Andrade-Campos A G, Martins J M P and Thuillier S 2019 Strain 89 1-18.
[10] Wisselink H H, Niazi M S and Huetink J 2011 Validation of advanced material models using the crossdie test 15th International Deep Drawing Research Group Conference 2011.
[11] ISO 12004-2 2008 Determination of forming-limit curves - Part 2.
[12] Banabic D, Barlat F, Cazacu O and Kuwabara T 2010 Int. J. Mater. Form. 3 165.
[13] ISO 6892-1 2016 Tensile testing - Part 1.
[14] ISO 16808 2014 Determination of biaxial stress-strain curve by means of bulge test with optical measuring systems.