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Chapter 6

Experiments

The aim of this chapter is to introduce the experiments, which are needed for the identification and validation of the constitutive laws. The results of these experiments and a discussion of the experimental conditions are given in the subsequent chapters. For differentiating the functionality of the introduced experiments, three categories are defined:

- Fundamental experiments
- Complementary experiments
- Validation experiments

The fundamental experiments give the experimental input data for the calibration of the material model (see chapter 7) and the failure model according to the state of the art. In this work, the results and the evaluation procedure of these experiments are assumed to be reliable and therefore are not investigated.

The complementary experiments are introduced for generating additional input data for the material and the friction model calibration. An ideal complementary experiment shows a high sensitivity concerning one parameter of the material or friction model. As opposed to the fundamental experiments, the measured data of these experiments does not lead directly to the desired model parameter. For the parameter identification a comparison between the prediction of the simulation and the measured data is necessary. Suitable quantities are selected, which are sensitive with respect to the investigated model parameter. Finally a value for the model parameter is chosen, which gives the best prediction of the measured data on the basis of the selected quantities. This procedure is referred to as indirect method. The application of this method requires the determination of all the other model parameters in advance. Provided, the insensitivity of a model parameter with respect to the prediction of the measured quantities is proven, it is possible to apply the indirect method without knowing this parameter. This exception allows determining the unknown model parameters sequentially.
Finally additional validation experiments are proposed in order to validate the predictive capability of the material and friction models. Furthermore, these experiments are applied for the validation of the failure criteria. The results, obtained from these experiments are not taken into account for the model calibration.

One should consider that the introduced classification of the experiments (fundamental, complementary and validation experiments) generally depends on the applied constitutive laws. The classification, shown in this chapter, results from the constitutive laws, which are used in the subsequent chapters.

Generally, the usage of a standard set of complementary and validation experiments is recommended, which simplifies the material logistics, the execution of real and simulation based experiments and the postprocessing. In this paragraph, some key requirements for the design of these experiments are summarized.

- Deviations between the manufactured die face and the CAD data have to be avoided; otherwise the expressiveness of the experiments is reduced.
- The experiments should be suitable for all steel grades and aluminum alloys comprised in a car body.
- In order to minimize the computation time of forming simulations, a rigid tool behavior during the forming operation should be assumed. To avoid the violation of this assumption, an adequate tool stiffness has to be assured.
- The size of the specimen should be as small as possible in order to limit the expenses for purchasing material, logistics and measurements. Additionally, a small dimension of an experiment also has a positive effect regarding the computational cost of the related simulation based investigations.
- Today, shell elements are widely used for modeling the sheet metal of forming simulations. These elements can be applied, if the tool radius divided by the sheet thickness does not go below a value of 1.5. The tool design should consider this limitation. On the one hand, the applied sheet thickness should be minimal for avoiding the violation of shell element discretization restrictions. On the other hand, the availability of thin high strength steels could be limited.
- In order to avoid differences between the experiment and the simulation model, caused by touching up the binder zone, a material flow between the binder and the die should be avoided.

Consequently, tools which are applied for the series production of parts are not recommended for the identification and validation of constitutive laws, as the tryout of the tools and wear lead to deviations with respect to the CAD data. Furthermore, these tools are designed for a specific material and thickness.

An experiment is suitable for the identification or validation of material models, friction models and failure criteria, if and only if reproducible results are
obtained. It is recommended to use quantities for these investigations, which can be directly obtained from real experiments. Examples are material failure, the sheet thickness, the springback effect, the press force and the strain field on the part surface.

The reproducibility of the experiments has to be analyzed before comparing the results of the experiments with the simulation. It is recommended to perform at least three experiments under the same conditions and to select one of them as a reference for further investigations. The minimum deviation between the measured result and the mean of all experiments, which have been performed under the same conditions, is used as selection criteria. Applying mean values for the description of an experimental result could lead to non-physical states. This statement is of particular importance, if several quantities are measured based on a single experiment.

6.1 Fundamental experiments

6.1.1 Tensile test

The tensile test is a standardized experiment (EN ISO 6892-1) for the determination of the stress-strain relation under an uniaxial stress state. The specimen is loaded in direction of the tensile axis. Due to this load case, the corresponding eigenvalues of the stress state (principal stresses) within the specimen are zero, apart from the eigenvalue, associated with the tensile direction. Both, the applied tensile force and the elongation of the material are recorded while the experiment runs.

![Tensile test diagram](image)

Figure 6.1: Tensile test; Left: Specimen of the experiment; Right: Schematic relation between the true stress $\sigma$ and the true strain $\epsilon$ [80].

The stress state is computed in the current configuration, i. e., the Cauchy (or true) stress is identified. For the determination of the Cauchy stress from the tensile force and the measured elongation in tensile direction, plastic incompressibility is assumed $A_0l_0 = Al (A = wt)$, which implies the preservation of the
CHAPTER 6. EXPERIMENTS

volume. Expression (6.1) gives the relation between the Cauchy stress and the measured quantities:

\[ \sigma = \frac{F}{A} = \frac{Fl}{A_0l_0}. \]  
(6.1)

The index 0 refers to the initial state. The corresponding logarithmic (or true) strain in direction of the tensile axis is shown by (6.2). In this case, the material time derivative of this strain measure is equal to the rate-of-deformation [60]:

\[ \epsilon = \int_{l_0}^{l} \frac{dl}{T}, \dot{\epsilon} = D. \]  
(6.2)

Commonly, the plastic hardening (flow curve) is derived from the relation between the plastic strain and the stress state as shown by figure 6.1 (right). By a rising load, the specimen elongates uniformly. However, at a material specific strain level, diffuse necking occurs, which is accompanied with a non uniform elongation of the specimen. The above introduced expressions are only valid as long as the specimen is uniformly elongated. Unfortunately, due to this limitation, the maximum measurable equivalent plastic strain for the stress-strain relation is lower than that one occurring at industrial parts [89].

Additionally, the uniaxial stress states and \( R \) values (6.3) for the calibration of the yield locus are obtained from this experiment:

\[ R = \frac{\dot{\epsilon}_m}{\dot{\epsilon}_\xi_\xi}. \]  
(6.3)

On the basis of an uniaxial stress level below the yield strength, the Young’s modulus and the Poisson’s ratio can be determined.

6.1.2 Bulge test

A quadratic shaped specimen is clamped between the binder and the die (figure 6.3). The material flow in the binder zone has to be avoided, which is achieved by a sufficient binder force and a drawbead. These tool components are rotationally symmetric. Instead of a punch, oil is applied as a media for the forming process, which avoids the influence of friction apart from the die radius where the motion is negligible. The sheet metal is formed by an increasing level of oil pressure (figure 6.2)[89].

At the top of the dome, a biaxial stress state is induced. During the forming process, the deformation field in the region of the top of the dome and the oil pressure is recorded. Nowadays, optical measurement systems are available for the determination of a time dependent deformation field [90]. The exploitation of the measured data enables the computation of the associated strain field. If the ratio between the sheet metal thickness and the bulge diameter is small,
bending stresses can be neglected [91] and consequently, it is possible to deploy the membrane theory for the determination of the biaxial stress state

\[ \sigma_b = \frac{pR}{2t} \]  

(6.4)

According to this relation, the biaxial stress state at the top of the dome depends on the oil pressure \( p \), the curvature \( \frac{1}{R} \) and the thickness \( t \) of the sheet metal at the corresponding location. Expression (6.4) is valid, if both principal stresses are assumed to be equivalent \( (\sigma_b = \sigma_1 = \sigma_2) \) [92]. Furthermore, the application of (6.4) implies the assumption that the shape of the dome in the pole zone is spherical. Originating from the assumption of plastic incompressibility, the strain in thickness direction is computed from principal strain values of the sheet surface \( (\epsilon_1, \epsilon_2) \):

\[ t = t_0 e^{\epsilon_3}, \epsilon_3 = -(\epsilon_1 + \epsilon_2). \]  

(6.5)

The determination of the pole curvature is still a subject of research. One solution is to fit a sphere in the pole region for determining the curvature. Another solution is the application of a quadratic response surface instead of a sphere for the approximation of the pole surface [93]. On the basis of the bulge test a flow curve can be obtained, which does not show the limitation of the tensile test, as much higher strain levels can be reached before a material failure occurs. It has
to be mentioned that this flow curve refers to the biaxial stress state. Today, the biaxial flow curve is usually transformed to the space of the uniaxial flow curve. Finally, both flow curves are combined to a flow curve describing the hardening effect even for high strain levels. For this procedure an isotropic hardening of the material is assumed. An approach for this transformation is the application of the equivalent plastic work relation \[94\]. If the hardening behavior of the material depends on the stress state, the isotropic hardening assumption might not be suitable. In such a case, the biaxial flow curve serves a valuable contribution for the calibration of an anisotropic elasto-plastic hardening model. Finally, the bulge test gives a biaxial stress state and an additional R value (6.6) for the calibration of the yield locus:\(^1\):

\[
 r_b = \frac{\dot{\varepsilon}_{yy}}{\dot{\varepsilon}_{xx}} \tag{6.6}
\]

### 6.1.3 Miyauchi test

For the generation of an approximately pure shear stress state, the Miyauchi test can be performed \[96\]. The definition of a pure shear stress state is given by \[62\]:

\[
\sigma_1 = |\sigma_3|, \sigma_2 = 0, \sigma_1 > \sigma_2 > \sigma_3. \tag{6.7}
\]

The eigenvalues \(\sigma_i\) of the stress tensor are assumed to be sorted ascending in expression (6.7). Figure 6.4 illustrates the specimen of the test, which is subdivided into the zones A,B,C for the explanation of the experiment.

![Miyauchi Test](image)

**Figure 6.4**: Miyauchi Test; Left: State before performing the experiment; Right: State after performing the experiment.

The external force \(F\) is acting, homogeneously distributed, in the zones A and B, causing a shear deformation in zone C. Figure 6.4 illustrates both, the initial state and the deformed state of the specimen. A fixture is needed, which is able to clamp the specimen sufficiently in these zones and enables to perform the test in a tensile testing machine. Optical measurement systems allow determining directly the time dependent deformation in zone C. On the basis of the measured deformation, the strain field is computed. The shear stress is obtained by applying

\(^1\)Aretz shows in his work \[95\] that the Bulge test might not generally be suitable for the determination of the value of \(r_b\).
\[ \tau = \frac{F}{2ht}. \] (6.8)

The evaluation of the experimental data leads to a flow curve with respect to the shear state and gives another stress state for the yield locus calibration. In case the material shows a pronounced anisotropic hardening, the experiment could be applied for the calibration of an elasto-plastic model, which takes this effect into account.

### 6.1.4 Nakajima test

The Nakajima test [81] is applied for the analysis of the onset of localized necking for different strain states. An alternative experiment has been proposed by Marciniak, which is not introduced here. Both experiments are standardized (ISO 12004-2).

![Nakajima Test](image)

**Figure 6.5**: Nakajima Test; Left: State before performing the experiment; Right: State while performing the experiment.

**Figure 6.6**: Nakajima Test; Specimen of the experiment.

The specimen is clamped between a rotationally symmetric binder and die. A material flow in the binder zone is avoided by a drawbead and a sufficient binder force. Usually, the Nakajima test is performed in specially designed testing machines. In this case, the forming operation can differ from the standard forming process (see chapter 3). Commonly, the binder and the die remain in a fixed position after the binder closing stage. The sheet metal is formed by a moving
spherical punch. Figure 6.5 illustrates the geometry of the tool and figure 6.6 the specimen. Different strain states are obtained by the variation of the specimen width \( w \) (figure 6.6). The deformation field is recorded during the forming process, which enables to compute a time-dependent strain field on the surface. Friction affects the results of the Nakajima experiment. A suitable lubricant has to be deployed for reducing the effect of friction as much as possible [97]. For the determination of the limit strain before localized necking occurs, different methods have been proposed. Two of these methods are the position-dependent determination (ISO 12004-2) and time-dependent determination. Thereby, the time-dependent method proposed by Volk [98] is based on the thinning rate of the sheet metal in the necking zone. If localized necking occurs, the thinning rate in the necking zone increases significantly. This effect is taken as a criterion for the determination of the forming limit. The forming limit curve (FLC) is created on the basis of the determined forming limits with respect to different strain states.

6.2 Complementary experiments

6.2.1 YLIT-Experiments

The Yield Locus Identification Tools (YLIT) have been developed jointly by ThyssenKrupp Steel Europe and BMW. The YLIT-Experiments are performed to generate additional data for determining the best possible yield locus shape with respect to the considered steel grade. Two basic geometries are used:

- Spherical punch
- Cubic punch

All experiments consist of a rotationally symmetric die and binder. The YLIT-1-TKSE comprises a spherical punch and the YLIT-2-TKSE a cubical punch with fillets. The geometry of the YLIT-2-TKSE and YLIT-3-BMW is similar but different in dimension. The punch geometry of the YLIT-1-TKSE and the YLIT-4-BMW is identical; however the blank geometry is different. Additional information regarding the experiments is given in [99].

During the forming process, the specimen is clamped between the binder and the die. The forming process is identical to the standard process (chapter 3). However, these experiments can be performed in a testing machine for Nakajima experiments. In this case, the kinematical sequence of the tools can differ from the standard process (see section 6.1.4). While the specimen is formed, its deformation is recorded. On the basis of the deformation field, the strain field is computed a posteriori. For the investigation of the yield locus, the strain state of the material points are considered, which are finally located in the necking zone. Apart from the strain state, the maximum drawing depth according to the FLC is also determined. Both, the strain state and the drawing depth are compared with
6.2. COMPLEMENTARY EXPERIMENTS

Figure 6.7: YLIT-3-BMW; Left: State before performing the experiment; Right: State while performing the experiment.

Figure 6.8: YLIT-4-BMW; Left: State before performing the experiment; Right: State while performing the experiment.

Figure 6.9: YLIT-Experiments; Specimens of the experiments.
the prediction of the simulation. The term drawing depth describes the maximum deformation of material points of the specimen with respect to the drawing direction at a given time during the forming operation. The maximum possible drawing depth is limited by the occurrence of a material failure (maximum drawing depth). The aim of this experiment is to search a yield locus shape, which leads to an accurate prediction of the measured quantities (indirect method). For obtaining the desired sensitivity of the yield locus shape on the prediction of the strain state and the drawing depth, the width of the rectangular specimen has to be optimized. As the measured data is determined before the elastic springback occurs, the measured strain field can be directly compared with the simulation result.

6.2.2 Bending experiment

For the investigation of the Young’s modulus a bending test is proposed. A rectangular specimen is clamped between the binder and the die (figure 6.10). The specimen is bent by the punch movement. As long as the gap between the die and the punch is larger than the sheet thickness, the influence of friction is not expected to be significant.

After the forming operation, before the punch is moved back to the initial position, the internal forces of the specimen are in equilibrium with the contact forces between the sheet and the tool surface. The movement of the punch to the initial position induces a new equilibrium state, which is accompanied with a deformation of the specimen (springback). The final geometry of the specimen is quantified by an angle $\alpha$, as the zones A and C are not affected by the bending
6.2. COMPLEMENTARY EXPERIMENTS

Consequently, the angle $\alpha$ reflects the springback behavior of the specimen. The springback effect is directly proportional to the bending radius $r_d$ \cite{88}. Hence, for maximizing it and for minimizing the risk of reaching discretization limitations of shell elements, a high value for the bending radius is recommended \cite{86}. Basically, an arbitrary alignment of the formed specimen is possible to evaluate the springback behavior. Most important is to choose an alignment, which allows a reproducible determination of the springback (angle $\alpha$). In this thesis, the zone of the formed specimen, which is located between the binder and the die during forming, is clamped in the measuring fixture. Figure 6.12 illustrates the measuring fixture for the determination of the angle $\alpha$. However, this type of alignment implies the influence of the gravity on the determined bending angle, which is expected to be small. The sensitivity of measured angle $\alpha$ with respect to the gravity depends on the stiffness of the formed specimen. Thereby, the stiffness is mainly affected by the initial thickness of the specimen. The thicker the material, the less influence is expected by gravity. Nevertheless, this effect should be investigated in advance before any comparison between measured and predicted angles.

![Figure 6.12: Bending experiment; Left: Definition of the angle $\alpha$ and the zones A, B and C; Right: The applied measuring fixture.](image)

6.2.3 Friction experiment

For the investigation of the frictional behavior between, the sheet metal and the tools, it would be necessary to determine the stress distribution in the contact zone. Today, it is very difficult to measure the desired stress distribution during a forming process. Therefore, another approach is chosen in this work. The validity of the Coulomb friction model is assumed and the model parameter $\mu$ is determined by an inverse approach. The sensitivity of this experiment concerning the model parameters of the stress-strain relation will be shown in chapter 8. The dependency of the frictional behavior with respect to the contact pressure, the temperature and the relative velocity between the contact surfaces is neglected. Nevertheless, if a more advanced model for the description of the frictional behavior exists and its parameters are known, the proposed experiment could be applied for validation purpose. Figure 6.13 illustrates the proposed experiment. According to figure 6.14, the rolling direction of the specimen is chosen to be
perpendicular to the symmetry plane. The specimen is taken from the coil under preserving the as-delivered condition regarding the lubricant. Only in the center of the specimen the lubricant film is removed for inducing a grid for the strain measurement. However, this zone is not in contact with the tool surface and therefore the removal of the lubricant film does not affect the results of the experiment. During the forming process the specimen is clamped between the binder and the die. The sequence of the tool movement is identical to the standard forming process, which is shown in chapter 3. For the inverse determination of the model parameter $\mu$, the strain state is measured at position $P$ (figure 6.14) at the top surface. Thereby, the model parameter $\mu$ is adjusted in order to obtain a simulation based prediction of the strain state equal to the measured one. In order to maximize the dependency of the friction on the measured strain state, the relative movement between the sheet and the punch radius should be maximized. The desired property of the experiment is obtained by choosing $R_p$ and $d_{bp}$ (distance between the binder and the punch contour) sufficiently large. The experimental setup, used in this thesis, does not allow measuring the strain state during forming. Hence, the strain field is analyzed after tool opening. Under this condition, it is necessary to take the effect of the springback on the strain field into account. As a consequence, the forming simulation has to be complemented by a springback simulation in order to compare an equivalent mechanical state of the formed specimen.

![Figure 6.13: Friction experiment; Left: State before performing the experiment; Right: State after performing the experiment.](image)

### 6.3 Validation experiments

#### 6.3.1 U-Profile experiment

Generally, the deformation of car body parts, caused by the springback effect, is complex. It is a combination of side wall curl, torsion, flange and side wall rotations. The effect is mainly determined by the geometry, the material and production process of the part. Especially double-curved-part regions increase the geometrical stiffness and therefore reduce the springback effect.
6.3. VALIDATION EXPERIMENTS

Figure 6.14: Friction experiment; Left: Specimen of the experiment; Right: Shape of the specimen after the forming operation.

Figure 6.15: U-Profile experiment; Left: State before performing the experiment; Right: State after performing the experiment.

Figure 6.16: U-Profile experiment; Left: Specimen of the experiment; Right: Shape of the specimen after the forming operation.
For the validation of material and friction models based on the springback effect, a u-profile experiment is proposed (figure 6.15). The geometry of this experiment maximizes the springback effect because of the single-curved geometry and shows a complex deformation except from torsion. The forming process of this experiment comprises a binder closing and a stamping stage. A detailed description of the kinematical sequence of the tools is omitted here, as it is a standard forming process like introduced in chapter 3. In this work, the rolling direction of the specimen is chosen to be perpendicular to the symmetry plane (figure 6.16 (left)). Another orientation of the rolling direction with respect to the symmetry plane could give further information regarding the predictive capability of the material model. During forming, a relative movement between the sheet metal and the tool surface occurs. Hence, friction could affect the forming process. The equilibrium state of the formed sheet after tool opening will be referred to as actual geometry. If the material flow is homogeneous in length direction, the cross sections perpendicular to this direction with respect to the actual geometry are approximately identical. For obtaining the desired homogeneous material flow during the forming process, a drawbead is recommended, which is suitable for all considered materials. Without such a drawbead, slight disturbances of the lubricant distribution or geometrical defects, caused by the touch up procedure can lead to an inhomogeneous material flow. Consequently, it is sufficient to analyze a cross section for characterizing the actual geometry as shown by figure 6.17. For the analysis of the springback effect, the actual geometry has to be aligned. As the top surface (figure 6.15 (right)) can be approximately described by a plane, it is recommended to align the actual geometry with respect to this zone. In order to reduce the data, needed for quantifying the springback effect, the quantities side wall rotation, side wall curl and flange rotation are introduced (figure 6.17). The reference points A',B',C',D' and E' are derived under the assumption that the shrinking, caused by the springback effect, is negligible. If this assumption holds, the position of A' is determined by equating the developed length of SA and SA'. The remaining points B',C',D' and E' are identified in the same way.

The influence of the gravity on the actual geometry is minimized by aligning the length direction of the u-profile parallel with respect to the gravity acceleration. A comparison of the experimentally determined quantities with the prediction of the simulation enables to validate the applied material and friction model. A key requirement for comparing the simulation result with the measured data is the identity of the material flow. If deviations occur, the material flow of the simulation has to be adjusted according to the measured one.

6.3.2 Hole extrusion experiment

For the validation of the forming limit curve (FLC) with respect to low $\alpha$ values ($\alpha = \dot{\epsilon}_2/\dot{\epsilon}_1$), the hole extrusion experiment is proposed (figure 6.18). The specimen of the experiment comprises holes of different diameters $d_i$. 
6.3. VALIDATION EXPERIMENTS

Figure 6.17: U-Profile experiment; Quantification of the springback effect.

Figure 6.18: Hole extrusion experiment; Zone of the FLC validation.
The length direction of the specimen is, in this thesis, chosen to be parallel to the rolling direction. During the forming phase, the specimen is clamped between the binder and the die (figure 6.19 (left)). Subsequently, the hole is extruded by the punch (figure 6.19 (right)).

![Figure 6.19: Hole extrusion experiment; Left: State before performing the experiment; Right: State after performing the experiment.](image)

![Figure 6.20: Hole extrusion experiment; Specimen of the experiment.](image)

The center of the hole should lie on the rotational symmetry axis of the punch. In order to comply this condition, an additional fixture is needed, which supports the alignment of the specimen and clamps it during the binder closing phase. The kinematic sequence of the tools of this experiment is identical to the standard forming process, shown in chapter 3. The failure mode localized necking leads to a lower bound with respect to the hole diameter, which will be referred to as $d_{\text{min}}$. If the diameter $d_i$ is chosen to be smaller than $d_{\text{min}}$, the hole extrusion will lead to localized necking. This diameter $d_{\text{min}}$ is identified experimentally, by analyzing the onset of localized necking visually. It should be mentioned that depending on the investigated material this experiment can also lead to the failure mode fracture. However, in this thesis such materials are not treated. Subsequently, the hole diameter is varied in steps of 0.5mm. The manufacturing procedure of the hole can affect the onset of localized necking. A standard piercing operation leads to an additional material hardening of the sheet metal on the edge of the hole. The FLC is not suitable for the consideration of this effect. Hence, for the validation of the FLC another method for the manufacturing of the hole is needed. The mentioned hardening effect is avoided, if the hole is manufactured by a milling process. For the validation of the FLC, the diameter $d_{\text{min}}$ is also determined based on the simulation. If the predicted value of $d_{\text{min}}$ is coincident with experimentally identified value, the FLC is able to reflect the localized necking regarding the considered strain state. For this indirect validation of the FLC, the parameters...
6.3. VALIDATION EXPERIMENTS

of the material and the friction model have to be determined in advance.

Nevertheless, if the hole is manufactured on the basis of a standard piercing process, the experimental result could be used for the validation of failure models, which takes the local hardening effects of trimming operations into account.

A similar experiment is described in the ISO/TS 16630. The objective of this experiment is to determine the limiting hole expansion ratio, which is given by

\[ \lambda = \frac{D_h - D_0}{D_0} \]  

\[ (6.9) \]

\(D_0\) is defined as the initial hole diameter. In order to identify \(D_h\), the specimen has to be observed during the forming process and the punch travel has to be stopped as soon as the material failure has extended through the thickness of the specimen. The advantage of the hole extrusion experiment, introduced in this thesis, is the possibility of evaluating the specimen a posteriori. Consequently, any observation of the specimen during the forming operation is not necessary, which simplifies the experimental setup.

### 6.3.3 Cylindrical deepening experiment

Finally, a validation experiment of the FLC regarding a strain state, which can be characterized by an \(\alpha\) value slightly above 0 (figure 6.21), is introduced.

Figure 6.21: Cylindrical deepening experiment; Zone of the FLC validation.

Figure 6.22 shows the experimental setup of the experiment. During the forming process, the square shaped specimen is clamped between the binder and the die. The movement of the punch, the die and the binder is equal to the standard forming process described in chapter 3.

The objective of the experiment is to determine the maximum drawing depth limited by the onset of localized necking. Thereby, the movement of the press ram and the punch force are recorded. As the material flow between the binder and the die is prevented, the above mentioned strain state is induced in the side wall zone. Provided, a material failure occurs in this zone, the experiment can be applied for an indirect validation of the forming limit curve. The validation is performed by comparing the simulation based prediction of the maximum possible drawing depth with the experimentally determined maximum drawing depth. For this
Figure 6.22: Cylindrical deepening experiment; Left: State before performing the experiment; Right: State while performing the experiment.

Figure 6.23: Cylindrical deepening experiment; Specimen of the experiment.

validation, the parameters of the material model and the friction model have to be identified in advance. As it is difficult to observe the development of localized necking during the forming process, the maximum drawing depth is determined indirectly.

The beginning $t_0$ of the forming operation is determined by the increasing punch force and the onset of localized necking $t_1$ is assumed to be coincident with the force maximum. The difference between the onset of localized necking and the fracture is assumed to be small in terms of the drawing depth$^2$. As the progress of the ram movement is recorded, it is possible to derive the maximum drawing depths on the basis of $t_0$ and $t_1$.

$^2$An investigation of the material response beyond the onset of localized necking is given in [100].