Characterization and Simulation of High-Speed-Deformation-Processes*

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Abstract

The combination of the processes deep drawing and electromagnetic pulse forming is a promising way to cope with the ever higher complexity of new sheet metal designs. A co-operation between the Institute of Materials Science (IW) of the Leibniz Universität Hannover and the Institute of Applied Mechanics (IFAM) of the RWTH Aachen is investigating these processes both experimental and in simulation. Aim is the characterization of the combined process. Therefore the material properties of the investigated aluminum alloy EN AW 6082 T6 have to be determined quasi-static as well as at high speed. These properties are then used as a basic for the simulations. Anisotropic behaviors as well as dynamic hardening effects are investigated in the quasi-static state. Several experiments for analyzing "Bauschinger" respectively "Ratcheting effects" have been conducted resulting in a new measuring set-up for thin sheets. For the determination of high speed forming limit diagrams a novel testing device on the basis of the Nakajima-test has been developed allowing for strain rates of approximately 10^3 s^{-1}. Both testing methods are described in this paper; the results are then used to adapt the simulation models for the combined processes.

The high speed deformation process is simulated by means of finite elements using a material model developed at the IFAM. The finite strain constitutive model combines nonlinear kinematic and isotropic hardening and is derived in a thermodynamic setting. It is based on the multiplicative split of the deformation gradient in the context of hyperelasticity. The kinematic hardening component represents a continuum extension of the classical rheological model of Armstrong–Frederick kinematic hardening which is widely adopted as capable of representing the above metal hardening effects. To prevent locking

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of the simulated thin sheets a new eight-node solid-shell finite element based on reduced integration with hourglass stabilization developed at IFAM has been used. With these features it was possible to simulate the Bauschinger effect obtained by the previous experiments.

Keywords

deep drawing, simulation, material properties

1 Introduction

It is known that the processing limits of single processes can be enhanced through a combination of them [1] [2] [3]. Complex deep drawing geometries for example can be processed through a combination of superplastic forming above the recrystallization temperature with a subsequent cold forming process [1]. Superplastic forming allows for forming complex structures while the following conventional deep drawing process in conjunction with strain hardening gives the required mechanical properties. Experiments with pultruded tubes showed that a combination of electro-hydraulic pre-strain with further quasi-static forming can enhance the ultimate strains at lower yield stresses [4].

Throughout the last decades researchers have proven that the formability of all kind of materials can be improved due to high speed deformation processes [5]. El-Magd et al. tested light metals (Al-, Mg- and Ti-alloys) and steels at quasi-static and dynamic loading between 10^{-4} 1/s and 5 x 10^{3} 1/s and proved an increase in flow stress and formability at higher strain rates [6] [7].

For the characterization and simulation of this new field of combined quasi-static and high-speed-deformation-processes the determination of material properties for both processes is essential. The special mannerism of the combined processes investigated within this project is very complex thus not only dynamic and static properties, hardening behaviors and forming limits have to be specified but also the different load paths and strain rates have to be included. While re-loading a specimen on the same load path has no influence on the initial flow stress of a DC06 steel concludes the re-loading in opposite direction in a decrease of the initial flow stress [8]. An unbalanced loading ($\sigma_{mean} \neq 0$ MPa) for instance results in a summation of the realized strains [9]. These effects are called the „Bauschinger”- respectively the „Ratcheting”-effect.

With increasing availability of fast computer hardware the finite element method is used more and more effectively to predict and simulate material behavior. In order to reduce computational time, a new efficient finite element technology is developed. To simulate this, the use of a purely isotropic hardening model (expansion of the yield surface) is not sufficient. Therefore, a finite strain constitutive model which combines nonlinear kinematic and isotropic hardening, based on the multiplicative split of the deformation gradient, developed in a recent work by Vladimirov et al. [10], is used in this work. The papers Choi et al. [11], Dettmer & Reese [12], Hakansson et al. [13], Menzel et al. [14], Svendsen et al. [15], Wallin et al. [16] are dealing with this subject.

Beside the dynamic material properties an appropriate model has to consider forming limits for all appropriate load paths and, especially in this case, strain rates. Forming limit diagrams respectively the forming limit curves are normally used to describe the forming limits of one material. Within this diagram it is possible to determine the maximum deformation a material can bear for a certain combination of major and minor strain, the load path.

2 Material characterization

The following paragraphs focus on the development of testing methods used for the material characterization within the scope of this project. Investigated were the evaluation of dynamic hardening effects and high-speed forming limits of thin sheet metals.

2.1 Dynamic material properties

For describing dynamic hardening and softening effects of metallic materials a variety of testing methods is available. Torsion or bending tests can be used to describe these effects with the possibility of testing thin sheet materials without the risk of buckling or the like. The problem with this type of testing is that the results have to be processed further to gain the material properties equivalent to the commonly used tensile testing method. While cyclic tension-compression testing gives the possibility to determine the Bauschinger and Ratcheting effect directly the experiment set-up has to be adapted to prevent buckling of the specimens whilst compressive loading. To circumvent the problem of buckling two different methods are used in recent years. The first possibility is to use guidings the second is to miniaturize the specimens. While the first requires adequate lubrication and tolerances of the guiding the latter puts high demands on the measuring method. For the testing of the thin rolled sheets of the Aluminum alloy EN AW 6082 T6 used within this project micro specimens together with a micro tension-compression testing device make Kammrath & Weiss have been used. The advantage of said device is the possibility of online testing inside the institutes SEM. The geometry of the used specimens and the testing device are shown in Figure 1.

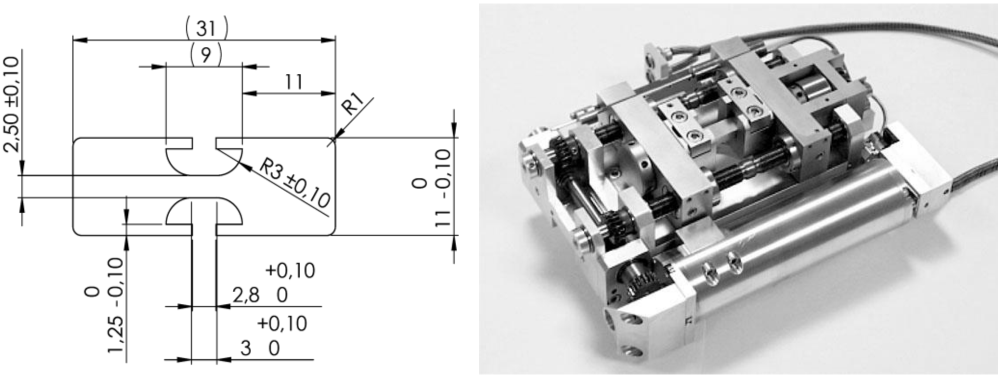

Figure 1: *Drawing and Dimensions of the specimens in mm (left) and picture of the testing device (right / Source: www.kammrath-weiss.com)*

To identify appropriate specimen dimension tests with measuring lengths of 10, 6 and 4 mm have been conducted. After inspection of the specimens only a measuring length of 4 mm showed adequate compression strains of up to 5 % without buckling. To ensure compression tests without buckling a measuring length of 3mm had been chosen for the following experiments.

After setting the specimen dimensions cyclic tension-compression tests inside a SEM were made. The testing inside the SEM was done due to the lack of a strain measuring device suitable for this kind of specimens. The device itself only has the possibility to measure the load and displacement of the clamps. While the calculation of the according stress is easy the conversion of the measured clamp displacement for getting the strain inside the specimen is not possible. Within the SEM it was possible to measure the actual strain by controlling the displacement of prominent areas on the surface of the specimen. A disadvantage of this method is that while the measurement is extensive the test has to be stopped for the time being. Thus the strains can only be determined incrementally. The resulting load-displacement plots of the testing device and the according stress-strain plots are shown in Figure 2. The first results have then been used for simulation of the dynamic behavior of the aluminum sheets in section 3.

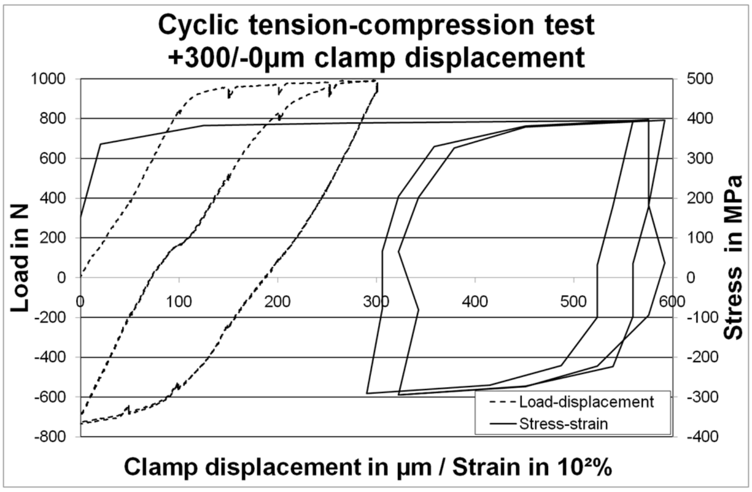

Figure 2: *Load-displacement and stress-strain curve of the testing inside the SEM*

Due to the lack of information needed for preparing the simulation between the SEM-measurements and the difficulties of getting an accurate measurement, a new method of measuring strains had to be looked for. In cooperation with the Laser Zentrum Hannover an electron speckle pattern interferometer was found as the best option for measuring strains online. The new experiment set-up is currently in the trial phase. The results of the new experiments will be published as soon as possible.

2.2 Investigations of high-speed forming limit diagrams

The knowledge of the formability of a material is a requirement for defining a production process. In sheet metal forming the forming limit diagram (FLD) is a means to characterize the maximum deformation a material can withstand prior to failure. Within the FLD the forming limit curve (FLC) depicts the maximum deformation to failure for different states of in-plane strains and stresses such as deep drawing, uniaxial state of stress, plain strain or plain state of stress. There are several procedures available for defining forming limit curves [17]. The most commonly used procedure is the Nakajima-test where a punch deforms a specimen clamped between a blank holder and the drawing die until fracture. The Nakajima-test is being standardized within the EN ISO 12004-2. The punch speed is defined at 1,5mm/s which is according to the hydraulic testing devices used. For defining forming limit curves adapted to high-speed deformation processes new testing methods have to be developed.

To simulate deformation speeds equal to those at electro-magnetic pulse forming a punch speed of 100m/s or higher has to be applied. Recently published developments e.g. by Kim et al. report punch speeds of around 20m/s [18]. While these experiments already show a change in the FLDs for the tested materials, the punch speed still is at least one power of magnitude lower than is needed to simulate deformations equal to those in electro-magnetic pulse forming. Within this project it is anticipated to develop a novel testing device that is able to test at strain rates of $1000s^{-1}$ to $4000s^{-1}$ with the according punch speeds of 100m/s to 400m/s.

There are several possibilities to provide the energy needed to perform a Nakajima-test at these high speeds or strain rates like energy of rotation or hydraulic energy, as used for the experiments by Kim et al. [18]. While most of them are able to provide sufficient energy they require special equipment and machinery or big storage for saving the energy. A testing device (Figure 3) was developed within this project which increases deformation speed using conservation of momentum. A drop weight hits the impulse device and accelerates the punch until it hits the integrated stopper at the aimed penetration depth. Springback of the punch is not prevented but so far is to be considered as uncritical.

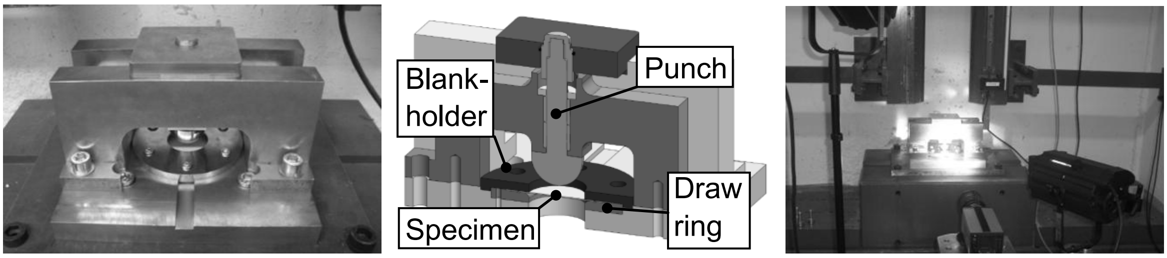

Figure 3: *Impulse device (left), CAD-model sectional view (middle) and test set-up (right)*

The testing was filmed via high-speed camera at 12500Hz to measure the punch displacement and the according speed as well as the occurring spring back. First tests with a drop weight of about 90kg and a drop height of 3m resulted in a max. punch speed of more than 90m/s. The impulse device and pictures of the high-speed camera are shown in Figure 4.

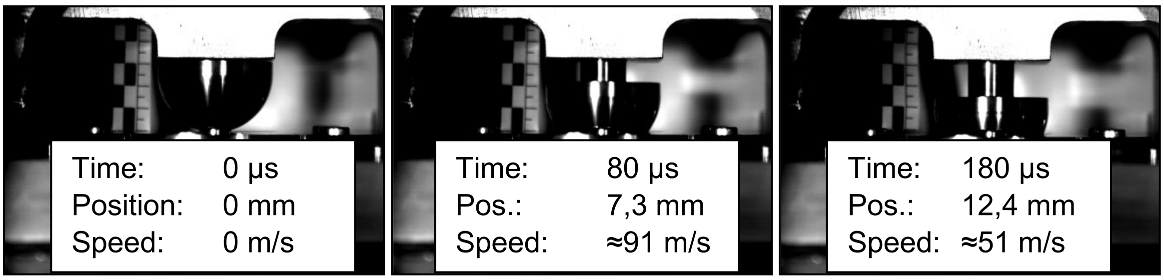

Figure 4: *Punch displacement of the impulse device during high speed forming*

According to EN ISO 12004-2, circular blanks with 100mm diameter in four different geometries were tested. The four geometries match the deformation states deep drawing ($\varphi 2 = -\varphi 1$), uniaxial tension ($\varphi 2 = -2\varphi 1$), plane strain ($\varphi 1=0$) and uniform stretch drawing ($\varphi 2 = \varphi 1$). Aluminum thin-sheets of the alloy EN AW 6082 T6 with 1mm thickness were used. Additionally, hot rolled three-layer composite sheets made of EN AW 5754 with core layers of steel (1.4008) or titanium (grade 1) were used to examine the device's adequacy for testing more complex materials. Circular blanks were water jet cutted, the different specimen geometries were eroded afterwards. A single Teflon spray coating has been used to reduce friction between tool and specimen. The cracked specimens of the first experiments with four different geometries are shown in Figure 5.

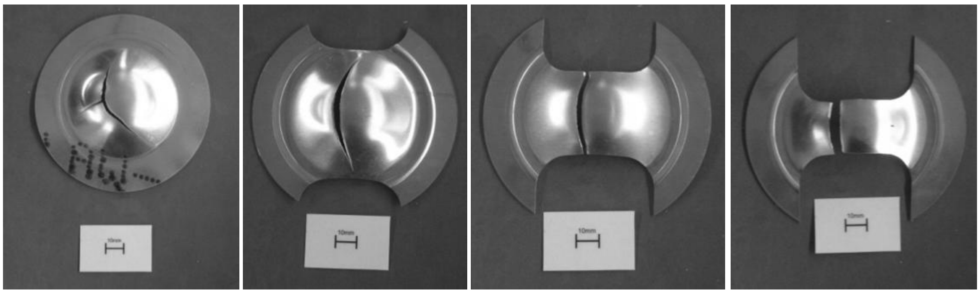

Figure 5: *Cracked specimens after testing*

The first step was to prove feasibility and to verify the demanded punch speeds. Evaluation of the optimal penetration depth of the tool in order to stop at beginning of crack opening as well as the strain analysis with an optical measurement system to deduce the forming limit diagrams will be subject of prospective investigations.

3 Simulation

The main goal is to build a new module for a realistic and numerically robust simulation with focus on contact modeling, the implementation of a plastic and a damage model and to demonstrate its applicability to simulate large deformations as the hardening behavior of materials e.g. the Bauschinger effect.

3.1 Material Modeling

The constitutive model is based on the multiplicative split $F_p = F_{pe}\,F_{pi}$ of the plastic deformation gradient into "elastic" and "inelastic" parts, $F = F_e\,F_p$ being the classical multiplicative split of F. As a result, a continuum mechanical extension of the classical rheological model of Armstrong-Frederick kinematic hardening [19] can be achieved.

The Helmholtz free energy per unit undeformed volume ψ is additively decomposed into the three parts $\psi = \psi_e(C_e) + \psi_{kin}(C_{pe}) + \psi_{iso}(\kappa)$. The first part ψ_e describes the macroscopic elastic material properties. The second term ψ_{kin} corresponds to the elastic energy stored in dislocation fields due to kinematic hardening and vanishes if the kinematic hardening is zero. The third term represents elastic energy due to isotropic hardening, where κ is the isotropic hardening variable. The Helmholtz free energy is a function of the elastic right Cauchy-Green tensor $C_e = F_e^T F_e = F_p^{-T} C F_p^{-1}$ and the elastic part of the plastic right Cauchy-Green tensor is defined as $C_{pe} = F_{pe}^T F_{pe} = F_{pi}^{-T} C F_{pi}^{-1}$.

Inserting this in the Clausius-Duhem inequality $-\dot{\psi} + S \cdot (1/2)\dot{C} \geq 0$ results in a relation for the second Piola-Kirchhoff stress tensor S.

The derivation of the material model is suitably carried out in the intermediate configuration. For the numerical implementation of the constitutive equations it is, however, more appropriate to work in the undeformed or reference configuration.

The set of constitutive equations of the model in the reference configuration is summarized below [20]:

- Stress tensors

$$S = 2F_p^{-1}\frac{\partial \psi_e}{\partial C_e}F_p^{-T},\ \ X = 2F_{pi}^{-1}\frac{\partial \psi_{kin}}{\partial C_{pe}}F_{pi}^{-T},\ \ Y = CS - C_pX,\ Y_{kin} = C_pX \tag{1}$$

- Evolution equations

$$\dot{C}_p = 2\dot{\lambda}\frac{Y^D C_p}{\sqrt{Y^D\cdot(Y^D)^T}},\ \ \dot{C}_{pi} = 2\dot{\lambda}\frac{b}{c}Y_{kin}^D\ C_{pi},\ \ \dot{\kappa} = \sqrt{\frac{2}{3}}\dot{\lambda} \tag{2}$$

- Yield function

$$\Phi = \sqrt{Y^D\cdot(Y^D)^T} - \sqrt{\frac{2}{3}}\left(\sigma_y - R\right),\ \ R = -Q(1-e^{-\beta\kappa}) \tag{3}$$

- Kuhn-Tucker conditions

$$\dot{\lambda} \geq 0, \Phi \leq 0,\ \ \dot{\lambda}\Phi = 0 \tag{4}$$

3.2 Finite element technology

Resent research focuses on the large deformation version of a new eight-node solid-shell finite element based on reduced integration with hourglass stabilization [21]. The major problem of low-order finite-elements used to simulate thin structures like sheet metal is locking, a nonphysical stiffening effect. Therefore in our recent solid-shell formulation the enhanced assumed strain (EAS) as well as the assumed natural strain (ANS) concept are implemented to circumvent locking. To cure transverse shear locking the corresponding transverse shear terms evaluated at locking-free sampling points are interpolated within the element domain. The same procedure applied to the transverse normal strain cures curvature thickness locking. For the EAS concept, the derivation is based on the well-established two-field variational functional

$$g_1(u,E_e) = \int_{B_0}\tilde{S}(E):\delta E_c\,dV + g_{ext} = 0 \tag{5}$$

$$g_2(u,E_e) = \int_{B_0}\tilde{S}(E):\delta E_e\,dV = 0 \tag{6}$$

which depends on the displacement vector u and the enhanced Green-Lagrange strain tensor E_e. In this enhanced strain tensor, the strain in thickness direction is enriched linearly. E_c is the compatible Green-Lagrange strain tensor. The EAS concept hence simplifies to a scalar equation, which leads to an efficient and robust element formulation.

Further important key points to improve the efficiency of the hourglass stabilization are different Taylor expansions with respect to the shell director.

The hourglass kernel C^{hg} depends on the material behavior in the integration point. The results of the following structural analysis carried out in ABAQUS have been obtained by means of this new eight-node-solid-shell element.

3.3 Uniaxial stress-strain test

As presented above, a large deformation elastoplastic material model with combined non-linear kinematic and isotropic hardening. It should describe the Bauschinger effect which belongs to the most characteristic phenomena of the hardening behavior of metals. The Bauschinger effect is defined by the fact that straining in one direction reduces the yield stress in the opposite direction.

Based on the experimental results of the Institute of Materials Science, Leibniz University Hanover, the model has been validated by fitting its parameters. A cycle of uniaxial tension/compression is shown in Figure 4, which depicts a good agreement between test and simulation data.

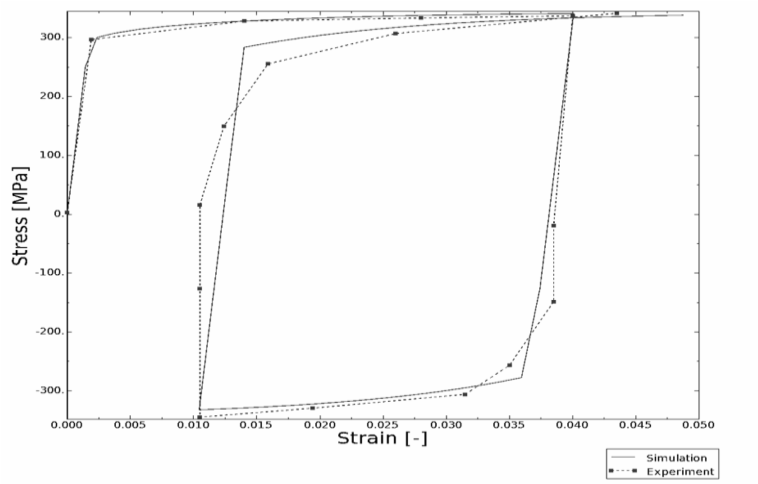

Figure 4: *Fit of material model for EN AW 6082 T6 sheet with thickness 1 mm, combined hardening*

According to the procedure used in [10], first the model is fitted based on the flow curve by using only kinematic hardening. This means, the isotropic hardening parameters β and Q are set equal to zero. At the second step, the fitting is performed by using only the isotropic hardening parameters. The kinematic hardening parameters (b and c) have in this case zero values.

Using this method, we obtain four “start” values for the hardening parameters. But as shown in Figure 4, only a combination of the four hardening parameters provides a good fit to the experimental data. The finally identified set of material parameters are: $\sigma_y = 296\ MPa,\ c = 2000\ MPa,\ Q = 11\ MPa,\ b = 70$ and $\beta = 200$.

Although a small deviation between experimental and simulation data is observed the correlation between the results can be considered to be very good. Certainly we need more complex (e.g. multiaxial) experiments to fully validate the model.

4 Discussion

The cyclic micro tension-compression tests beneath the critical unsupported length allow preventing buckling without any support. Any influence caused when using a support can be avoided. Main disadvantage is the small measuring length, which complicates mechanical or optical strain measurement on the specimens’ surface. The first measurements of the Bauschinger effect using a SEM were problematic due to the lack of information between each measurement, a new method for measuring the strains using an electron speckle interferometer is tested right now. With this new measuring method together with the micro testing module it will be possible to realize the aimed compression-tension measurements at thin sheet metals.

The new device for high-speed Nakajima-testing enables punch speeds of 91m/s with the expected maximum speed being much higher. A disadvantage of this method is the strong springback of the punch. This causes a second impact of the tool on the tested sheet and may influence the results. More experiments are needed for verification. Testing of monolithic materials is possible. Composites are problematic for testing because failure mechanisms as delamination cannot be detected easily. The lubrication seems to be less important than in quasi-static testing but again more experience is needed for verification.

The simulation of dynamic effects shows good correlation with the experiments. The material model considering both kinematic and isotropic hardening works satisfactorily. Obviously, more experiments are needed to fully validate the model.

5 Summary and future work

The results of experiment and simulation can be referred to as follows:

- The modified cyclic micro tension-compression test is feasible for testing dynamic hardening effects
- The used measuring method needs to be optimized to gather more data
- The material model used for simulation allows to reproduce the experimental data satisfactorily but more experimental data is needed for further optimization
- The developed impulse device is capable of high-speed Nakajima-testing with punch speeds of 91 m/s and more
- The experimental setup works for monolithic materials; composite sheets cannot be tested satisfactorily due to their multiple failure mechanisms
- The lubrication seems to have less influence than in quasi-static testing, further experiments are needed for verification

Determination of forming limit curves and diagrams by means of optical measurement systems will be one focus of future investigations. The results of the simulation can only be improved with a better experimental data base thus more dynamic testing with improved strain measurements will be a further emphasis.

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