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New method for stress determination based on digital image correlation data

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ABSTRACT

Accurate material characterisation of anisotropic yielding behaviour for modern sheet metal requires the testing under multiaxial stress conditions like in the shear test or plane strain test. While most approaches include time-consuming finite element simulations for evaluation of inhomogeneous stress distributions, this paper shows a new method to determine stress data based directly on digital image correlation data. This accurate and efficient semi-analytical method can be used in direct stress analysis or inverse material parameter identification schemes as well. The methodology will be described and exemplarily results of the plane strain test and the shear test will be discussed.

1. Introduction

For process analysis and validation of sheet metal forming processes the numerical simulation with finite element analysis (FEA) is state of the art. In industry, simulations assist users in widening the process windows of forming operations and can lead to smarter material usage due to better knowledge of achieved product properties [1]. In this context, it is essential to properly model the material behaviour during forming to obtain accurate and reliable predictions [2].

An important aspect of material modelling is the anisotropic yielding behaviour of sheet metal, which is known to have a significant influence on simulation results [3]. This is due to the fact, that during a deep drawing operation a number of complex stress conditions occur. Fig. 1 shows this exemplary for a drawn cross cup, including distribution and portion of relevant stress conditions. In addition to quite simple uniaxial tension (1), a high proportion and therefore relevance for other stress states such as biaxial tension (3), plane strain (2) and shear (4) is obvious.

Because of this, more complex yield criteria than Hill'48, which uses only information from the uniaxial tensile test, are used nowadays. Advanced yield criteria such as Yld2000-2d [4], Vegter [5] or BBC2000 [6] are able to consider the above mentioned multiaxial stress conditions. This complex experimental test data has to be evaluated in order to identify the parameters of these criteria. Therefore, the main challenge for obtaining reliable material parameters is the evaluation of heterogeneous strain fields in complex specimen geometries and the determination of corresponding inhomogeneous stress fields. This challenge cannot be solved with analytical equations but rather requires more advanced methods for data evaluation in general.

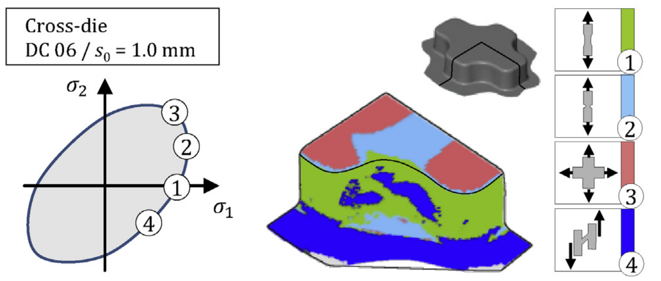

Fig. 1. Different stress conditions in deep drawing of a cross-cup.

2. Stress evaluation strategies

As stress cannot be measured directly, stress evaluation strategies have to use a measurable quantity, e.g. strains, and compute the stress based on this information.

Regarding determination of heterogeneous strain distributions, optical full-field measurement using digital image correlation (DIC) has recently been improved and is now widely used for contact-free deformation measurement [7]. In DIC a stochastic speckle pattern is applied on the surface of a test object and recorded in image sequences during testing and deformation. Each speckle on the object's surface is subdivided into small subareas called facets, which are tracked in order to determine the displacement and strain fields. However, the evaluation of heterogeneous stress fields is still challenging and requires advanced complementary testing procedures to gain additional information about stress states. For instance,

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X-ray diffraction as applied by Güner et al. can be used for stress measurements on plane strain tension and shear specimen [8]. These methods require expensive equipment and are therefore not satisfactory for industrial applications. Hence, analytical or numerical strategies for stress data determination are of major interest and will be described in the following.

2.1. Analytical stress evaluation

In the analytical approaches, the experimentally measured force and an averaged strain over the plastic area are directly used to determine the stress states by solving simple equations.

Most strategies focus on the homogenization of the stress field in the specimen in order to use analytic equations for stress data evaluation. For complex material tests like the shear test, this causes inaccuracies. During shearing, the initial shear stress becomes superposed by a tensile stress component in the direction of the tool movement [9]. For large deformations also the boundaries become dominant, invalidating the assumption of a homogenous stress field.

Another popular and simple strategy is to use analytical correction factors like proposed by Flores et al. [10] for the plane strain region and An et al. for the shear region [11]. These strategies are based on certain assumptions about the yield function that are taken into account by the ratio of the two principal stresses. All analytical approaches are inherently inaccurate for experiments with heterogeneous deformation fields, but are still favoured due to their simplicity and efficiency.

2.2. Numerical stress evaluation

The improvement of optical full field strain measurement led to numerical evaluation strategies, which are now commonly used for the determination of material parameters [12].

Finite element analysis is very common for numerical stress evaluation, where virtual tests are iteratively compared to experimental results and deviations are minimised. Using this technique, it is possible to calibrate models on tensile tests with heterogeneous deformation fields [13]. Additionally, measured strain fields can be directly used for stress analysis. A suitable scheme for this is the virtual field method, in which stress components are iteratively computed for a complete deformation field [14]. Alternatively, an efficient modification is a cutting-line approach, where strain is evaluated over integration paths on a specimen in order to determine an internal load used for parameter identification. Marth et al. evaluated a path on a tensile specimen with a radial return method for von Mises plasticity to determine the post necking behaviour of sheet metal [15].

However, numerical procedures have high computational costs, especially for the iterative procedures in the finite element method scheme. In addition to the extensive modelling effort, a strain mapping procedure is required. Moreover, the utilised stress integration procedures, requiring a minimum time step for robust analysis, are an impediment for computing speed. Furthermore, determination of strain fields with DIC is unstable for strains smaller than 0.01 [7]. Hence, there is a great demand for a fast and robust stress analysis based on DIC measurements.

3. New method for stress analysis

The new computational procedure of stress analysis on measured DIC data will be briefly described in the following. Contrary to other approaches, which apply time consuming and interference-prone return mapping schemes for elasto-plastic stress computation on strain data, this alternative scheme takes advantage of one equation of plasticity — the associated flow rule.

3.1. Stress determination approach

The associated flow rule (Eq. (1)) defines the relationship between the change of plastic strain $\mathbf{d}\varepsilon^{\mathbf{p}}$ and the derivative of the yield function *f*, which is equal to the normal $\boldsymbol{n}$ on the yield function:

$$d\boldsymbol{\varepsilon}^{p} = \lambda\cdot\frac{df}{d\boldsymbol{\sigma}} = \lambda\cdot\boldsymbol{n} \quad (1)$$

where λ is the plastic multiplier and $\frac{df}{d\boldsymbol{\sigma}}$ is the derivative of the current yield surface f with respect to the current stress σ. The normal $\boldsymbol{n}$ is related to one single and unique position on the plane stress yield surface, described by the stress condition $\sigma = \{\sigma_{xx}, \sigma_{yy}, \tau_{xy}\}^{T}$. With the assumption that finite and infinite changes of plastic strain are nearly equal ($\mathbf{d}\varepsilon^{\mathbf{p}} \approx \Delta\varepsilon^{\mathbf{p}}$) the left side of Eq. (1) is known because the continuously measured DIC data easily allows the calculation of incremental plastic strain $\Delta\varepsilon^{\mathbf{p}}$. Now, a derivative of the yield function $\frac{df}{d\boldsymbol{\sigma}}$ being collinear to $\Delta\varepsilon^{\mathbf{p}}$ has to be identified by a root-finding algorithm. The identified stress direction $\hat{\boldsymbol{\sigma}}$ describes the position on the yield surface, where the actual stress state $\sigma_{\mathbf{i}}$ of one measured DIC data point can be found. With the knowledge of the stress direction $\hat{\boldsymbol{\sigma}}$ the next stress state $\sigma_{\mathbf{i+1}}$ can be calculated assuming isotropic hardening (see Fig. 2a).

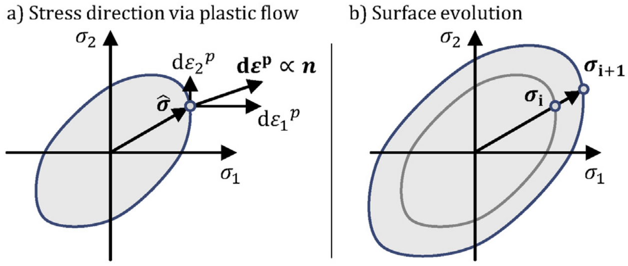

Fig. 2. Stress evaluation strategy.

The expansion of the yield surface starting from $\sigma_{\mathbf{i}}$ to $\sigma_{\mathbf{i+1}}$, as shown in Fig. 2b, takes place in relation to the corresponding amount of plastic work, identified in the uniaxial tensile test. Starting from the initial stress state $\sigma_{\mathbf{i}}$ and its corresponding yield surface, a subsequent yield surface is estimated by incrementally increasing the equivalent plastic strain ε^{p}_{eq} and the corresponding flow stress σ_{Y}. The estimated plastic work for this current increment dW_{est} is calculated using numerical integration with the trapezoidal rule and the determined stress direction $\hat{\boldsymbol{\sigma}}$:

$$dW_{est} = \frac{(\hat{\boldsymbol{\sigma}} \cdot \sigma_{Y}(\varepsilon^{p}_{eq}) + \sigma_{I})}{2}\cdot d\boldsymbol{\varepsilon} \quad (2)$$

where $\boldsymbol{\sigma}_{\mathbf{i}}$ is the initial stress state, $\sigma_{Y}(\varepsilon^{p}_{eq})$ is the current flow stress and $\mathbf{d}\varepsilon$ is the current strain increment. The actual state variables are calculated by determining an adequate equivalent plastic strain ε^{p}_{eq} for which the incremental plastic work in uniaxial tension dW_{Y}, as specified by the flow curve $\sigma_{Y}(\varepsilon^{p}_{eq})$, and the incremental plastic work dW_{est} is equal. The stress components in σ are calculated by multiplying normalised stress $\hat{\boldsymbol{\sigma}}$ and current yield stress σ_{Y}. The new variables for plastic strain ε^{p}_{eq} and the related stress state σ are stored for every measured DIC point and are used in the next calculation step for the new yield condition. Finally, the sheet thickness is updated based on the strain data and volume constancy. The described strategy can be used for every yield criterion and hardening behaviour.

3.2. Verification of the proposed method

The general suitability of the proposed stress field identification approach is subsequently shown for the uniaxial tensile test, see Fig. 3a. This is done by comparing the conventionally obtained analytical flow stress σ_{xx}, calculated by dividing the measured tensile force by the true cross section area, with the new method for stress analysis.

Fig. 3b shows a quite homogenous stress distribution based on the DIC analysis over the cutting line, which is in very good agreement with the analytical solution. The same accordance is observed for the stress–strain curve, see Fig. 3c.