Parameter identification of strain rate dependent hardening for sheet metals

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In this contribution we examine the influence of strain rate on the isotropic hardening of two sheet metals. The nominal strain rates vary between 0.0005 s\(^{-1}\) and 20 s\(^{-1}\) and the full field deformation is captured with the help of digital image correlation (DIC) technique. For modelling the strain rate dependent behaviour, we introduce a rate dependent part in the definition of the hardening stress, distinguishing between approaches that incorporate the rate dependency in an additive or multiplicative manner. The hardening laws are thereby embedded in a large strain plasticity framework based on the logarithmic strain space. The material parameters are identified both in a “direct” fashion, where the gap between constitutive equation and measured stress-strain curve is minimized and inverse, by using the finite element method (FEM) to generate force-displacement curves and the virtual fields method, which compares internal and external virtual work.

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1 Introduction

Proper material parameters play a crucial role in the simulation of forming processes. For the identification of these parameters oftentimes experiments with simple one-dimensional stress states are constructed resulting in homogeneous deformation fields. This allows a “direct” comparison of stress-strain curves between experiment and constitutive model. More sophisticated experimental setups yield heterogeneous deformation fields, allowing to address a wide variety of stress states and hence representing the material behaviour more thoroughly. To obtain material parameters from those experiments one needs more advanced identification strategies, like inverse fitting with FEM simulations or the virtual fields method (VFM). In the following, we identify parameters for rate dependent hardening models from uniaxial tensile tests with both approaches and compare the results to the direct identification.

2 Material modelling

The rate dependency is modelled by the incorporation of additional terms in the function of the yield stress \(\sigma_Y\). Generally speaking, the rate dependent and independent parts can be split multiplicatively, \(\sigma_Y(\dot{\varepsilon}^p, \dot{\varepsilon}^0) = \sigma_{Y,\text{stat}}(\dot{\varepsilon}^p)\hat{\sigma}_Y(\dot{\varepsilon}^0)\) and additively, \(\sigma_Y(\dot{\varepsilon}^p, \dot{\varepsilon}^0) = \sigma_{Y,\text{stat}}(\dot{\varepsilon}^p) + \sigma_Y(\dot{\varepsilon}^0)\), where in the case of the dynamic split the rate dependent part is unities, as indicated by the hat. For the “static” part we have chosen a generalized power law (Swift). The rate dependency is introduced through the models of Johnson-Cook, Cowper-Symonds (multiplicative) and Zerilli-Armstrong (additive).

Generalized power law: \(\sigma_{Y,\text{stat}}(\dot{\varepsilon}^p) = K \left[\varepsilon_0 + \dot{\varepsilon}^p\right]^n\), Johnson-Cook: \(\sigma_Y(\dot{\varepsilon}^p, \dot{\varepsilon}^0) = \sigma_{Y,\text{stat}}\left[1 + C \log \left(\frac{\dot{\varepsilon}^p}{\dot{\varepsilon}_0}\right)\right]\)

Cowper-Symonds: \(\sigma_Y(\dot{\varepsilon}^p, \dot{\varepsilon}^0) = \sigma_{Y,\text{stat}} \left[1 + \left(\frac{\dot{\varepsilon}^p}{\dot{\varepsilon}_0}\right)^{1/b}\right]\), Zerilli-Armstrong: \(\sigma_Y(\dot{\varepsilon}^p, \dot{\varepsilon}^0) = \sigma_{Y,\text{stat}} + b \left[\dot{\varepsilon}^p\right]^c\)

To incorporate large strain plasticity, we follow the approach established by [1] and [2]. Based on the logarithmic strain tensor \(E^0 = 1/2 \ln F^T F\), where \(F\) denotes the deformation gradient, a work-conjugate stress measure \(\hat{T}\) is calculated in a “small strain” fashion. The transformation to Lagrangian space, \(\hat{S} = \hat{T} : \hat{P}\), is achieved through a fourth order mapping tensor which is defined through the derivative of the logarithmic strain tensor w.r.t. the right Cauchy-Green tensor, \(\hat{P} = 20E^0/\partial C\).

Further details of the implementation of the large strain plasticity framework and the application to kinematic hardening and anisotropic plasticity can be found in [3] and [4].

3 Experiments

Two sheet metals have been considered for this contribution, DC04 and DP600, both with an initial thickness of 2 mm. The investigated nominal strain rates range from 0.0005 s\(^{-1}\) to 20 s\(^{-1}\) and for each rate and material three specimen were tested. To obtain displacement fields on the surface of the specimen, digital image correlation is used. The resulting stress-strain curves show rate dependent hardening behaviour for both materials, cf. Fig. 1. Comparing the evolution for DC04 and DP600, one can notice that increasing the strain rate for DC04 results in an increase in the initial yield stress (the curves are shifted towards higher stress), whereas for DP600 the curves only start to fan out with increasing strain.
4 Parameter identification

The parameter identification via FEM is often denoted as finite element model updating (FEMU) and consists of a finite element simulation that resembles the experiment. In this particular example the displacements at the edges of the specimen, measured with DIC, are prescribed in the FE simulation and the resulting reaction forces in tensile direction are used in the identification.

Neglecting body forces and accelerations, the principle of virtual work is expressed in the undeformed configuration as

\[
\int_{B_0} P(F) : \nabla_0 \delta u \, dv = \int_{\partial B_0^e} t_0 \cdot \delta u \, da \quad \text{for the virtual fields method (VFM).}
\]

Herein \( P \) denotes the first Piola-Kirchhoff stress, \( t_0 \) the traction forces and \( \delta u \) a virtual displacement field. If the virtual displacement field is chosen such that it is constant along the traction boundary \( \partial B_0^e \), it can be placed outside the integral and the external virtual work can be expressed with the help of the externally applied forces measured by the load cells, \( \delta W_{\text{ext}} = \delta u \cdot f_{\text{ext}} \). For the VFM, the deformation gradient is reconstructed on the surface of the specimen through the displacement field captured by DIC and enters the virtual work equation through the first Piola-Kirchhoff stress tensor. For the example at hand, the virtual displacement field is chosen as \( \delta u = [0, y]^T \), where \( y \) is the direction of tension. This results in an internal virtual work that is only a function of \( P_{22} \).

The different identification strategies all lead to similar material parameters with deviations among each other of less than 5%. Based on the root mean square errors, both materials are fitted best with the Zerilli-Armstrong model, though DP600 can also be represented quiet well with Johnson-Cook and Cowper-Symonds. For DC04 however, those models cannot depict the aforementioned shifting phenomenon, leading to unsatisfying fits.

5 Concluding remarks

In this work the methodologies of inverse material parameter identification through finite element simulations and the virtual fields method were used to identify model parameters for strain rate dependent hardening. For the two sheet metals under consideration, DC04 and DP600, an additive split of rate dependent and independent hardening parts for the yield stress, as expressed by the Zerilli-Armstrong model, show the best agreement to experimental data. Both inverse strategies find similar material parameters compared to a direct identification with only little deviation.

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