Proceedings of the 8th GACM Colloquium on Computational Mechanics
for Young Scientists from Academia and Industry
August 28–30, 2019 in Kassel, Germany

A nonlocal ductile damage model for high strength steels under dynamic multiaxial loading conditions

Marvin Nahrmann[1] and Anton Matzenmiller * [1]

[1]Institute of Mechanics, Dept. of Mechanical Engineering, University of Kassel, Mönchebergstr. 7, 34125 Kassel, Germany

Abstract. The high strength steel alloy HX340LAD (ZStE340) is investigated under quasistatic and dynamic loading conditions for different flat specimens. A thermo-viscoplastic constitutive model is applied to capture the temperature and strain rate dependent material characteristics. In order to consider the post-critical material behaviour, the model is enhanced with a nonlocal ductile damage approach. The predicted results exhibit a close agreement to the measured values leading to a successful verification of the model.

1 Introduction

Today's multi-material designs of lightweight car body structures are built upon a broad variety of different steel and aluminium alloys. The diverse material properties of these metals are tailor-made for the respective application areas. In order to ensure the occupant safety, a high tensile strength for the protection of passengers is required as well as a high ductility absorbing the crash energy in the crumpling zone by means of large plastic deformations. Microalloyed high strength steels (HSLA steels) provide a good material strength and ductility and are well suited for complex cold-formed vehicle body parts. Due to dynamic multiaxial loading conditions in the case of metal forming or vehicle crash, the finite element simulation of HSLA steel is still a sophisticated task. Particularly for high strain rates, the conversion of dissipated work into heat causes a locally significant temperature rise. Hence, a temperature and strain rate dependent constitutive model is applied for a thermo-mechanical coupled simulation. Moreover, a nonlocal ductile damage model is appended to capture the mesh independent post-critical material behaviour and enable a good prediction of the entire energy absorption potential.

2 Constitutive model for thermo-viscoplastic material behaviour

The temperature and strain rate dependent material behaviour of high strength steels is considered by the thermo-viscoplastic constitutive model comprehensively presented in [10]. The basic framework of the model is adopted from [4] and [5], whereby it is originally applied to the simultaneous hot/cold forging of metals–see [7]. In this contribution, only a moderate temperature range, from room temperature up to approximately 600 K is considered, which is sufficient to comprise the adiabatic heating for high strain rates. The constitutive equations of the thermo-viscoplasticity model are implemented as a user defined material model (*MAT_USER_DEFINED_MATERIAL_MODELS) into the commercial FE software LS-DYNA and include the temperature dependency of the Young's modulus, the initial yield stress, and the nonlinear isotropic hardening.
Adiabatic heating is taken into account by the Taylor-Quinney approximation, which determines the temperature increase by means of the viscoplastic stress power and the specific heat capacity c.

$$\dot{\theta} = \frac{\gamma_{\mathrm{TQ}}}{\rho\ c}\ \mathbf{T} \cdot \dot{\mathbf{E}}_{\mathrm{vp}}\ , \quad \gamma_{\mathrm{TQ}} = 0.90 \tag{1}$$

Here, the coefficient γ_{TQ} is specified to convert 90 % of the viscoplastic work into heat. The resulting thermo-mechanical coupled problem is solved by the staggered solution scheme, whereby the thermal problem is solved with a constant displacement field and the mechanical problem with fixed temperatures, respectively.

***Corresponding author:** post-structure@uni-kassel.de

3 Nonlocal ductile damage approach

The thermo-viscoplastic material model is coupled with a ductile damage approach based on continuum damage mechanics allowing the prediction of damage and failure caused by large plastic deformations. The concept of effective stresses is employed in order to obtain the CAUCHY stress tensor in the damaged (physical) space ${}^{\mathrm{a}}\mathbf{T}$ on the basis of the damage variable D and the CAUCHY stress tensor in the undamaged (effective) space $\mathbf{T}$. All internal strain variables shall be identical in both configurations, due to the strain equivalence principle–see [5]. The ductile damage growth is driven by the equivalent viscoplastic strain $\bar{\mathrm{E}}_{\mathrm{vp}}$, whereby the approach of LEMAITRE in [6] is applied, introducing the model parameter ε_{c} related to the damage initiation and ε_{f} for failure. The exponent n_{D} controls the course of the damage evolution.

$$ {}^{\mathrm{a}}\mathbf{T} = (1-D)\,\mathbf{T}\ , \quad D = \left\langle \frac{\bar{\mathrm{E}}_{\mathrm{vp}} - \varepsilon_{\mathrm{c}}}{\varepsilon_{\mathrm{f}} - \varepsilon_{\mathrm{c}}} \right\rangle^{n_{\mathrm{D}}} \ , \quad 0 \le D < 1 \tag{2} $$

The nonlocal option *MAT_NONLOCAL is inbuilt in LS-DYNA and based on the integral approach presented in [11] preventing the localisation of an arbitrary spatial field. In this contribution, the nonlocal formulation is applied to the damage variable D to maintain mesh independent outcomes–see also the investigations in [2]. Hence, the rate of the nonlocal damage variable $\dot{\bar{D}}(\mathbf{x})$ at the reference material point $\mathbf{x}$ is obtained by weighting the local damage rate $\dot{D}(\mathbf{y})$ at neighbouring points $\mathbf{y}$ over a certain region Ω of the continuum.

$$ \dot{\bar{D}}(\mathbf{x}) = \frac{1}{W(\mathbf{x})} \int_{\Omega} \dot{D}(\mathbf{y})\ w(\mathbf{x},\mathbf{y})\ \mathrm{d}\mathbf{y}\ , \quad W(\mathbf{x}) = \int_{\Omega} w(\mathbf{x},\mathbf{y})\ \mathrm{d}\mathbf{y} \tag{3} $$

For the implementation in conjunction with finite elements, the integral formulation is approximated by sums over the elements included in the integration region Ω that is determined by the characteristic length l_{c}–see Fig. 1 (left).

$$ \dot{\bar{D}}(\mathbf{x}) \approx \left[\sum_{i=1}^{N} \dot{D}_i\ w_i\ V_i \right] \left[\sum_{i=1}^{N} w_i\ V_i \right]^{-1} \ , \quad w_i = w(\mathbf{x},\mathbf{y}_i) = \left[1 + \left(\frac{\|\mathbf{x}-\mathbf{y}_i\|}{l_{\mathrm{c}}} \right)^{p} \right]^{-q} \tag{4} $$

Basically, a bell-curved function is assumed for weighting the local variable. The weighting function $w(\mathbf{x},\mathbf{y}_i)$ is evaluated at $\mathbf{y}_i$ for the elements $i = 1,\ ...,\ N$ in the integration region and is hard-coded in LS-DYNA with two model parameters, p and q, specifying its shape. Here, the values $q = 2$ and $p = 8$ are selected, leading to a broad localisation zone within the integration region. Note that this function is only valid in the integration area, so if $\|\mathbf{x}-\mathbf{y}_i\|/l_{\mathrm{c}} \le 1$–see Fig. 1 (right).
In order to enable the nonlocal formulation, the characteristic length l_{c} has to be greater than the element length in the damage zone. However, the determination of the characteristic length is still a sophisticated challenge. A measurement method for concrete is outlined in [3] on the basis of notched and unnotched tensile tests. In contrast to concrete, the material behaviour of high strength steels is much more ductile. Furthermore, it is well known that the damage and failure behaviour highly depends on the stress state–see [12]. Discussions on the internal length for ductile metals are made in [2] and [1], nevertheless, a general measurement technique has not established yet at all. In [13], the characteristic length is expected to relate to the damage mechanism. In the case of ductile metals, two different damage and failure mechanisms occur. The first is dimple rupture under hydrostatic loading, whereby internal voids are expanded and void coalescence leads to failure. The second damage mechanism is shear failure by means of void elongation within a narrow shear band. Thus, the nonlocal damage model is supposed to consider stress state dependency for the simulation of structures under multiaxial loading conditions.

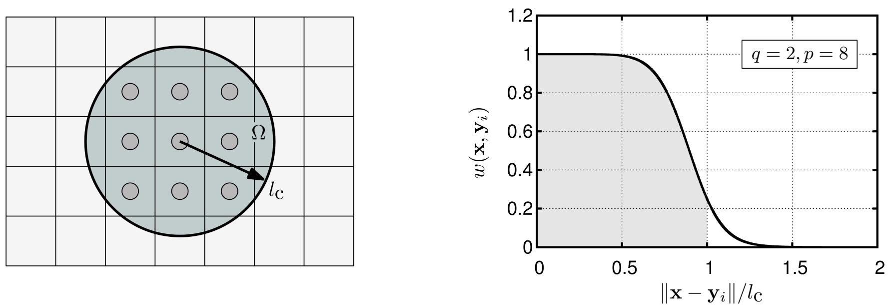

Figure 1. Integration region Ω determined by the characteristic length l_{c} (left), weighting function w (right)

4 Verification results for a high strength steel under dynamic multiaxial loading conditions

The thermo-viscoplastic material model with nonlocal ductile damage is verified for six flat specimens, made of the microalloyed high strength steel HX340LAD (ZStE340), for quasistatic (qs) as well as dynamic loading conditions under low (25 mm/s), medium (250 mm/s) and high velocities (2500 mm/s)–see Fig. 2. All model parameters of the thermo-viscoplasticity model are identified and listed in [10], whereby tensile test data from [9] and [8] as well as shear test data from [12] are employed. The parameters for the ductile damage approach and the nonlocal formulation are presented in Fig. 2 for all investigated specimens. Different damage model parameters are permitted for each specimen in the first instance, due to the absence of a stress state dependent nonlocal damage model. The characteristic length for every specimen is defined on the basis of the plastic zone prior to failure, leading to a similar extent of

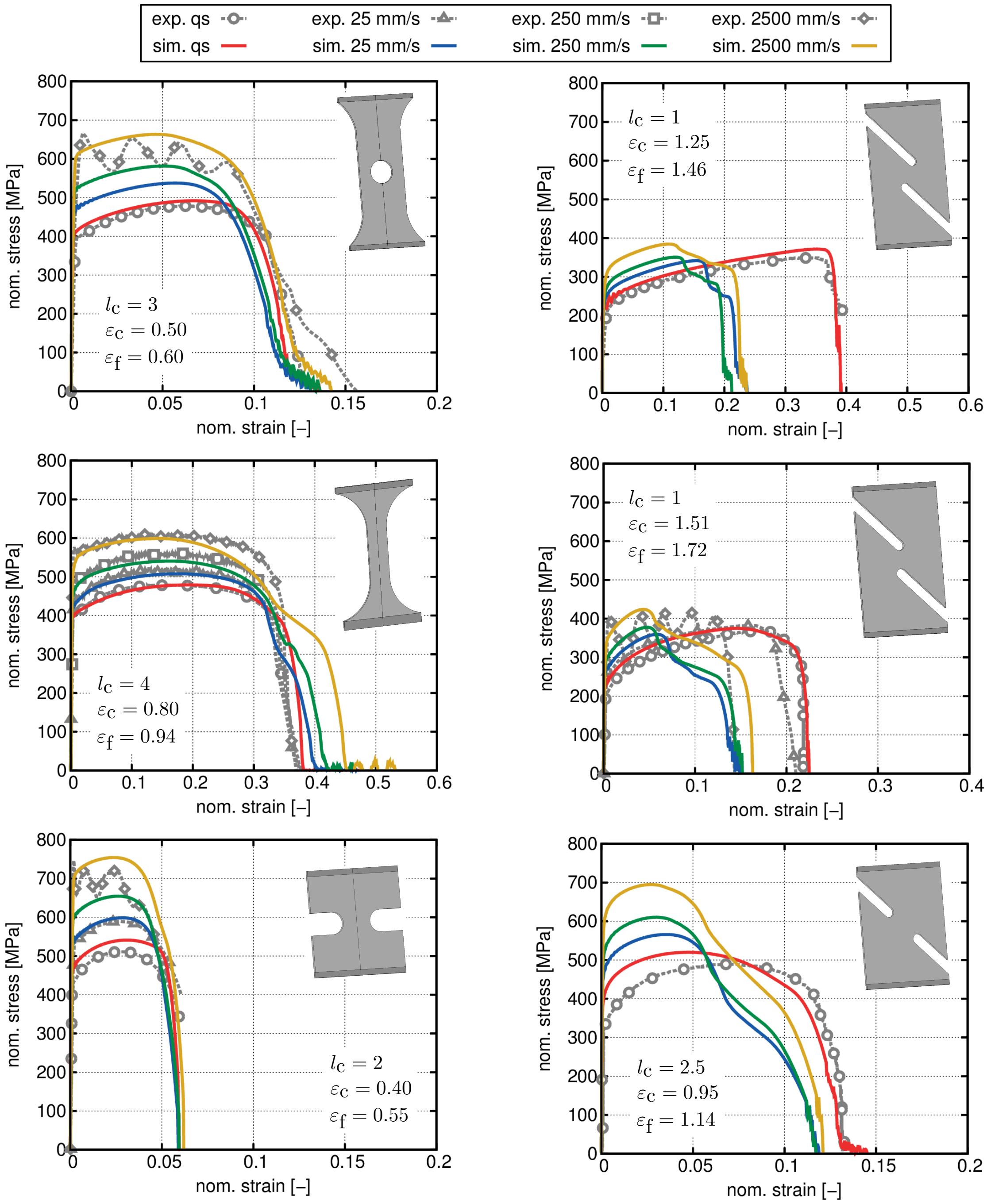

Figure 2. Simulation results compared to test data ([9],[12]) for the perforated, unnotched and notched tensile specimen (left column) as well as for the -20°, 0° and 45° shear specimen (right column)

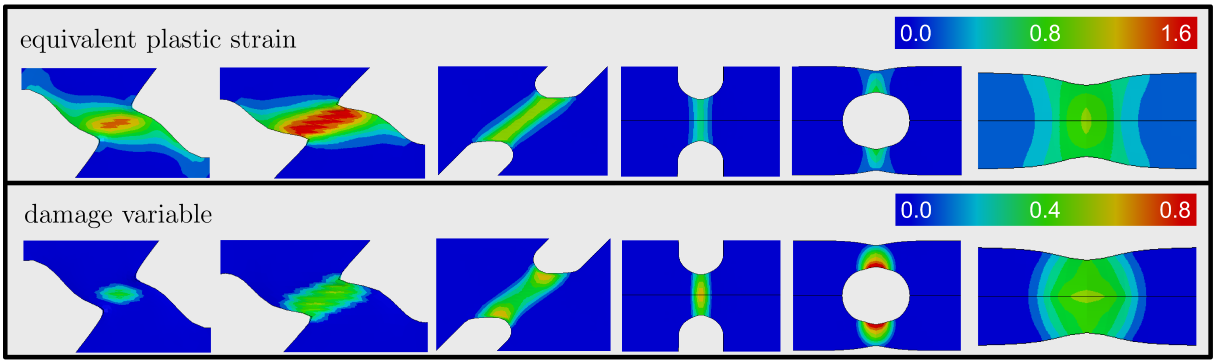

Figure 3. Spatial fields of the equivalent plastic strain and the damage variable prior to failure for the -20°, 0° and 45° shear specimen as well as for the notched, perforated and unnotched tensile specimen

high plastic deformations and damaged material–see Fig. 3. This results in noticeable different values for l_c, comparing tensile and shear test for example. The overall simulation results are in good correlation with the according test data for nearly all specimens and loading conditions. An interesting effect is the reduction of elongation for shear dominated high speed loading, recognisable in the experimental as well as in the predicted stress-strain courses–see right centred diagram in Fig. 2. A probable reason is the strong adiabatic heating in a narrow band resulting in thermal softening and premature failure.

References

[1] F. R. Ahad, K. Enakoutsa, K. N. Solanki, and D. J. Bammann. Nonlocal modeling in high-velocity impact failure of 6061-T6 aluminum. *International Journal of Plasticity* 55 (2014), pp. 108–132.

[2] F. X. C. Andrade, J. M. A. Cesar de Sa, and F. M. Andrade Pires. Assessment and comparison of non-local integral models for ductile damage. *Int J of Damage Mech* 23.2 (2014), pp. 261–296.

[3] Z. Bazant and G. Pijaudier-Cabot. Measurement of Characteristic Length of Nonlocal Continuum. *Journal of Engineering Mechanics* 115.4 (1989), pp. 755–767.

[4] C. Bröcker and A. Matzenmiller. An enhanced concept of rheological models to represent nonlinear thermoviscoplasticity and its energy storage behaviour. *Cont Mech Therm* 25 (2013), pp. 749–778.

[5] C. Bröcker and A. Matzenmiller. On the generalization of uniaxial thermoviscoplasticity with damage to finite deformations based on enhanced rheological models. *Technische Mechanik* 34 (2014), pp. 142–165.

[6] J. Lemaitre. A Continuous Damage Mechanics Model for Ductile Fracture. *Journal of Engineering Materials and Technology* 107 (1985), pp. 83–89.

[7] A. Matzenmiller and C. Bröcker. Thermo-mechanically coupled FE analysis and sensitivity study of simultaneous hot/cold forging process with local inductive heating and cooling. *International Journal of Material Forming* 5 (2012), pp. 275–300.

[8] G. Meschut and M. Gerkens. *Entwicklung einer Methode zum Nachweis der Einsetzbarkeit des Hochgeschwindigkeits-Bolzensetzen unter Berücksichtigung der Bauteileigenschaften*. Europäische Forschungsgesellschaft für Blechverarbeitung e.V., report no. 455. 2017.

[9] G. Meschut, O. Hahn, D. Hein, A. Matzenmiller, and A. Nelson. *Experimentelle und numerische Untersuchungen des Crashverhaltens hybridgefügter Verbindungen*. FOSTA report P958. 2015.

[10] M. Nahrmann and A. Matzenmiller. *Modelling and identification of coupled thermo-viscoplastic material behaviour with nonlocal ductile damage*. Proceedings of the 12. European LS-DYNA Conference, Koblenz. 2019.

[11] G. Pijaudier-Cabot and Z. Bazant. Nonlocal Damage Theory. *Journal of Engineering Mechanics* 113.10 (1987), pp. 1512–1533.

[12] A. Trondl, S. Klitschke, W. Böhme, and D.-Z. Sun. *Verformungs- und Versagensverhalten von Stählen für den Automobilbau unter crashartiger mehrachsiger Belastung*. FAT-Schriftenreihe 283. Forschungsvereinigung Automobiltechnik e.V. (FAT). 2015.

[13] V. Tvergaard and A. Needleman. Nonlocal effects on localization in a void-sheet. *International Journal of Solids and Structures* 18 (1997), pp. 2221–2238.