Higher-order plasticity formulation for metal forming processes

Citation for published version (APA):

Document status and date:
Published: 01/01/1999

Publisher Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:
• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher’s website.
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Introduction
Adopting a continuum approach, local plasticity formulations are capable of simulating the behaviour of metals to a certain degree. Specific phenomena can not be modelled properly, e.g. the intense localisation of deformation in case of shear bands. From a physical point of view these phenomena are attributed to the microstructural interactions, which are not described in the local approach. Furthermore, it is also known that the microstructure plays a key role in the ongoing miniaturization of forming processes. This research mainly considers the following aspects:
- ductile failure behaviour
- scale-size effects

Method
Yield function
Classical Huber-Mises plasticity is used, enriched with a ductile damage parameter $\omega_p$:
\[
F = \sqrt{3J_2} - \sigma_y \left[ 1 - \omega_p \right]
\]
where $\sqrt{3J_2}$ denotes the second invariant of the stress tensor, $\sigma_y$ a standard hardening rule.

Ductile damage evolution
The amount of ductile damage is related to the nonlocal effective plastic strain $\bar{\varepsilon}_p$, according to an exponential evolution law:
\[
\omega_p(\bar{\varepsilon}_p) = 1 - e^{-\beta \bar{\varepsilon}_p}
\]
Accordingly, the amount of ductile damage will gradually decrease the initial yield strength from its initial value ($\omega_p = 0$) towards zero ($\omega_p = 1$) upon complete failure.

Higher-order continuum
In addition to the equilibrium condition the nonlocal field is determined by solving the following partial differential equation of the Helmholtz type:
\[
\bar{\varepsilon}_p - \ell^2 \nabla^2 \bar{\varepsilon}_p = \varepsilon_p
\]
The Laplacian $\nabla^2 \bar{\varepsilon}_p$ implicitly incorporates an infinite series of higher-order gradients of $\bar{\varepsilon}_p$, which is consistent with a higher-order continuum approach to maintain the well-posedness of the problem [1]. Moreover, this type of equation has a nonlocal character [2], implying long-range interactions of a material point with its surrounding material.

Results
Length parameter
The length parameter $\ell$ is a material parameter, which governs the spatial interactions within the continuum (see figure 1).

Regularization
The local quantity $\varepsilon_p$ in figure 2 marks the plastic zone. The long-range interactions of $\bar{\varepsilon}_p$ into the elastic region allow the shear band to maintain a certain (finite) volume.

Evolution of failure
During the process of ductile failure two stages are noticeable:
- formation of the first and second shear band (1st row in figure 3)
- further localisation within the two shear bands (2nd row)

Conclusion
The presented gradient plasticity model is well capable of describing the process of ductile failure in a regularized fashion.

Future work
- Assessing the quality of the gradient model from a physical point of view
- Extension to geometrically nonlinear problems

References: