THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING IN SOLID AND STRUCTURAL MECHANICS

# Computational modelling of machining -

Mesh objective ductile damage modelling

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Cover:
Upper figure illustrates high-speed camera images of an experimental test of perforation of a Weldox 460 E steel plate with a blunt-nosed projectile from [**35**].
Lower figure illustrates a numerical simulation of the experimental test.

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# Abstract

To strengthen the competitiveness the manufacturing industry strives for a continuous development of cost efficient manufacturing processes and improved product quality. These research and development issues are addressed by increasing the implementation of simulation tools based on finite element method (FEM). To represent the material response during the machining process, reliable and well-defined constitutive and fracture models are required. In the current work the well-established and widely used visco-plastic Johnson-Cook (JC) constitutive model is utilized for the stress response in the material. To account for the ductile damage in the material the JC-fracture model is combined with the JC-constitutive model. However, the major drawback with the JC- fracture model is that it exhibits a pathological mesh dependence. Therefore, relating the local continuum damage theory with principles of maximum dissipation, combined with concepts from the phase field modeling, two different mesh objective damage models were derived. Numerical examples, reflecting the highly localized plastic shear deformations that occur in the vicinity of the cutting edge during machining, were utilized to validate and verify the mesh objective damage models. The general example, verifying the mesh objective strategy, considers the shearing of a pearlitic plate with structured mesh. The results indicate that the mesh dependence is removed when strain-rate and temperature dependence is excluded from the model. Additionally an investigation regarding the influence of element distortion was conducted. For this emphasis a hat specimen with unstructured mesh was subjected to severe shear deformation while neglecting the temperature and strain-rate dependence. The results show that realistic damage path is captured, and also quantitatively, a good agreement is obtained for the effective stress and plastic strain levels compared to literature. Extending the JC-constitutive model by incorporating visco-plasticity (and excluding the mesh objective enhancement), still results in a pathological mesh dependence which is contrary to what has been argued in literature. The perforation of a Weldox 460 E steel plate by a blunt-nosed projectile was used to validate the modeling. The numerical simulations were compared with results from literature and experimental findings and were found to be in a good agreement. Based on the numerical examples conducted the models are able to predict damage evolution at ductile fracture in a reliable manner. This enables a possibility to accurately evaluate the machining process with respect to operating parameters e.g. cutting force, temperature distribution, chip morphology and residual stresses. Hence, improving the understanding of the complex phenomena occurring during the machining process and the product quality while increasing the cost efficiency of the process.

Keywords: Mesh dependence, fracture modeling, ductile damage, visco-plastic Johnson-Cook, FEM, machining process, simulation tool

# Preface

The work presented in this thesis was carried out during 2013-2016 at the Department of Applied mechanics, Division of Material and Computational Mechanics at Chalmers Univeristy of Technology. The research was financially supported by The Ekmanska Foundation (Ekmanska stiftelsen) and the Swedish national research program FFI (Strategic Vehicle Research and Innovation), subarea sustainable production.
I would like to thank my supervisor Prof. Ragnar Larsson and my co-supervisor Prof. Lennart Josefson for their patience, invaluable guidance and encouragement.
I would like to take the opportunity to thank all my colleagues at the Division of Material and Computational Mechanics and at the Division of Dynamics for the nice working environment and interesting discussions. I would like to thank my friends, especially Adi Cutuk for the patience, understanding and support.
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Gothenburg, May 2016
Senad Razanica

# Nomenclature

| Symbol | Description | Unit |
|---|---|---|
| a, p | parameters in the Retcht-Ipson model | - |
| A | damage driven energy/force | $N/m^2$ |
| $A_c$ | elastic stored free energy to be released | $N/m^2$ |
| $A_f$ | the diffuse fracture area | $m^2$ |
| $A_T$ | the total damage driven energy | $N/m^2$ |
| $\sigma_y$, B, C, n | parameters in the Johnson-Cook constitutive model | Pa, Pa, -, - |
| $\bar{\mathbf{b}}$ | elastic finger deformation tensor | - |
| c | fracture energy parameter | - |
| $c_c, c_r$ | damage evolution parameters | - |
| $d_r$ | reference element size | m |
| $d_1 - d_4$ | parameters in the Johnson-Cook fracture criterion | - |
| D | damage variable | - |
| $\mathcal{D}$ | total dissipation rate | $N/sm^2$ |
| $\hat{\mathcal{D}}$ | the effective dissipation rate | $N/sm^2$ |
| $\hat{\mathcal{D}}_T$ | total dissipation | $N/m^2$ |
| $\hat{\mathcal{D}}_T^f$ | dissipated energy during the fracture process | $N/m^2$ |
| E | young's modulus | Pa |
| $\mathbf{E}_e$ | the elastic material operator | Pa |
| $\mathbf{f}$ | gradient of the yield function | - |
| $\mathbf{F}$ | total deformation gradient | - |
| $\dot{\mathbf{F}}$ | time derivative of the total deformation gradient | - |
| $\bar{\mathbf{F}}$ | elastic portion of the total deformation gradient | - |
| $\bar{\mathbf{F}}_p$ | plastic portion of the total deformation gradient | - |
| g | damage function | - |
| $g_c$ | the ductile crack surface energy release parameter | $Nm/m^2$ |
| G | elastic constant representing shear response | Pa |
| $G$ | dissipation potential due to diffuse crack surface propagation | $N/m^2$ |
| $\dot{G}$ | fracture dissipation rate due to diffuse crack surface propagation | $N/sm^2$ |
| $H_S$ | heaviside function | - |
| $\mathbf{I}_{dev}^{sym}$ | symmetric part of the deviatoric identity tensor | - |
| $\mathbf{I}^{sym}$ | symmetric part of identity tensor | - |
| J | volumetric component | - |
| $k$, $\dot{k}$ | state variables | -, 1/s |
| K | elastic constant representing volumetric response | Pa |
| l | current element length | m |
| $\mathbf{l}$ | spatial velocity gradient | 1/s |
| $\mathbf{l}_p$ | inelastic portion of the spatial velocity gradient | 1/s |
| $L_e$, $L_c$ | identical to, l and $d_r$ | m |
| m | progressive damage evolution parameter | - |
| $\hat{p}$ | effective pressure | Pa |

| Symbol | Description | Unit |
|---|---|---|
| $r$ | triaxiality | - |
| r | displacement of the shear loaded plane strain plate | m |
| R | reaction force response of the shear loaded plane strain plate | N |
| t, $t_c$, $t_f$ | actual, critical and failure time | s |
| V | velocity | m/s |
| $V_{bl}$ | ballistic limit velocity | m/s |
| $V_i$ | initial projectile velocity | m/s |
| $V_r$ | residual projectile velocity | m/s |
| $V_{rpl}$ | residual plug velocity | m/s |
| $\alpha$ | scalar damage variable | - |
| $\dot{\alpha}$ | rate of damage evolution | 1/s |
| $\psi$ | free energy in the (damaged) material | $N/m^2$ |
| $\hat{\psi}$ | the free energy of the effective (undamaged) material | $N/m^2$ |
| $\psi^{iso}$ | isochoric portion of the effective free energy | $N/m^2$ |
| $\psi^{vol}$ | volumetric portion of the effective free energy | $N/m^2$ |
| $\psi^{hard}$, $\psi^{mic}$ | hardening portion of the effective free energy | $N/m^2$ |
| $\kappa$ | the isotropic (damaged) hardening stress | Pa |
| $\hat{\kappa}$ | the effective isotropic hardening stress | Pa |
| $\lambda$ | the plastic multiplier | 1/s |
| $\phi$ | quasi static yield function | Pa |
| $\phi_\alpha$ | damage criterion for the evolution of the damage | - |
| $\tau$ | the damaged affected kirchhoff stress | Pa |
| $\hat{\tau}$ | the effective kirchhoff stress | Pa |
| $\hat{\tau}_e$ | the effective von Mises stress | Pa |
| $\hat{\tau}^{\triangle}$ | Green-Naghdi rate of the effective stress | $N/sm^2$ |
| $\overset{\square}{\hat{\tau}}$ | Oldroyd rate of the effective stress | $N/sm^2$ |
| $\dot{\epsilon}_0$ | reference strain rate for the Johnson-Cook models | 1/s |
| $\epsilon_f^p$ | plastic fracture strain | - |
| $\mu$ | damage multiplier | - |
| $\delta_S$ | diract-delta function | - |
| $\gamma$ | fracture area density per unit volume | $m^2/m^3$ |
| $\nu$ | poisons ratio | - |
| $\rho$ | density | $kg/m^3$ |

# Thesis

This thesis consists of an extended summary and the following appended papers:

| | |
|---|---|
| **Paper A** | R. Larsson, S. Razanica and B. Lennart Josefson. Mesh objective continuum damage models for ductile fracture. *International Journal for Numerical Methods in Engineering*, 2015; doi: 10.1002/nme.5152 |
| **Paper B** | S. Razanica, R. Larsson and B. Lennart Josefson. Mesh objective damage modelling at visco-plastic continuum response. *To be submitted for international publication.* |

The appended papers were prepared in collaboration with the co-authors. The author of this thesis was responsible for the major progress of the work in preparing the papers, i.e. took part in planning the papers, took part in developing the theory, performed all implementations and numerical calculations, and took part in writing the papers.

# Contents

# Part I
# Extended Summary

## 1 Background and Motivation

Key factors for the competitiveness of the manufacturing industry are their ability to rapidly realise new products and to make use of their manufacturing processes as effectively as possible. Despite the continuous process development still a considerable waste of material- up to 10 % of the workpiece volume might be removed to reach the final geometrical dimensions [**1**] of the component. There are also other difficulties which relate to the product quality, such as local fracturing, severe grading of mechanical properties with depth from the machined surface due to microstructural phase transformations coupled to temperature. Hence, there are tremendous incentives to fine-tune existing manufacturing processes, or to replace them with new and innovative ones, in order to obtain near-net-shape. Therefore it is important to optimize the whole manufacturing process, on a macro-level, with respect to distortion and surface integrity. However, obtaining desired product properties is achieved by maintaining control of processing parameters on micro-level, e.g. the creation of desirable compressive surface stresses in machined components, cutting forces, chip morphology, temperature distribution among others. In general, the manufacturing industry currently addresses these issues by increasing implementation of simulation tools based on finite element method (FEM) for the specific operations included in their processing chain [**1**], [**2**], [**3**], [**4**], [**5**]. However, to represent the machining operations the modeling of the ductile material response during the process is crucial. It has been shown that the reliability of the numerical results are strongly coupled to the viability of the adopted constitutive model to accurately describe the material deformation [**1**], [**2**]. Recently, primary focus has been highlighted on the development of damage and fracture models [**6**], [**7**]. The proposed approaches to model the material degradation are e.g based on local and non-local continuum damage models [**8**], [**9**], [**10**]. Different techniques have been employed within the local continuum framework, applying the Johnson-Cook (JC) fracture criterion [**11**], considering only the plastic failure strain as a indicator for damage [**12**] or using the fracture energy as a criterion [**13**]. However, it is well-known that the local continuum models exhibit a pathological mesh dependence when softening models are used and needs to be accounted for [**14**]. Besides the obvious focus related to individual process operations, these simulation tools could provide a first step towards a co-ordination of tools to simulate the whole manufacturing process chain. Where the emphasis on the interactions between the specific operation processes and their impact on the final product might be investigated in order to increase the understanding and the efficacy of the manufacturing process.
The present project will focus on two processes, turning and high speed cutting, where similar physical situations arise, high deformation rates inducing elevated temperature, large plastic deformations and narrow fracture zones. In the case of machining heterogeneous materials the interaction between different phases in the microstructure, experiencing elevated temperatures, lead to an additional complexity of the deformation process [**15**].

A better knowledge of the deformation process in this region will considerably improve the possibility to optimise these processes with respect to both the shape of the machined components, the tools and fixtures used.
The potential benefit foreseen is improved machined components in combination with more efficient and robust manufacturing technology. In practice, it could be envisaged that the intended simulation tools could be used to facilitate good shape control in combination with tailored surface properties, i.e. setting of surface residual stresses at controlled levels for enhanced fatigue performance in cases where e.g. bending is predominant.

# 2 Aim and limitations of the research

The main objective with the current PhD project concerns the modeling and simulation of the manufacturing process that involve separation of material, e.g. machining, turning, cutting based on the finite element method in order to optimise the processes. However, the reliability of the FE tools depend strongly on the constitutive and fracture model utilised. These models must be able to properly describe the severe material deformation and complex phenomena that occur in the vicinity of the cutting edge during the machining operation. Consequently, the key challenges comprise efficient, accurate and robust models accounting for temperature, hardening rate sensitivity and ductile fracture.
In the current work the main focus has been put on the modelling of ductile fracture and the rate dependence in the material, primarily for cutting processes. For this emphasis the well-established visco-plastic Johnson-Cook (JC) constitutive and fracture models are utilised. The ductile fracture model exhibits a pathological mesh dependence as it is formulated within the local continuum framework. Hence, in the present work the issue concerning the mesh dependence is investigated with the primary aim to remove this inherent behavior in local continuum damage models. The verification of the models has been done with respect to shear tests, a deformation mode that is predominant in machining and cutting. In order to confirm that the model predict reliable material response, a validation has been conducted based on tests from the literature where similar conditions occur as during machining e.g. perforation of a plate with a projectile. The numerical response has been compared with literature and experimental findings.

# 3 Machining and numerical modeling

Machining is a complex process as well one of the most common manufacturing processes for producing components, obtaining specific geometrical dimensions and surface finish defining the final product properties. Before machining is applied (often the last step in the production line) the specific components are formed, representing the desired geometrical shape while exceeding the dimensional and surface tolerance. However, after the machining operation the correct dimensions are obtained and the component is more or less finished. During this process a material portion called "chip" is removed from the workpiece using a cutting tool with higher hardness. Meanwhile a diversity of physical phenomena occur such as large elasto-plastic deformations, high strain rates, thermomechanical coupling, complicated contact conditions and chip separation. The major deformation during the machining operation, which occur at the vicinity of the tool tip, is concentrated within three different zones; primarily, secondarily and tertiary deformation zones illustrated in Figure 3.1. During the high deformation rates involved in these processes a severe localised shear deformation occur in the primarily deformation zone. This leads to a high temperature increase in this region which is a consequence of the large amount of heat generated due to energy dissipation from the highly localised plastic deformation in the vicinity of the cutting edge. However, in the secondary deformation zone the workpiece material would either slide or stick on the cutting tool surface.

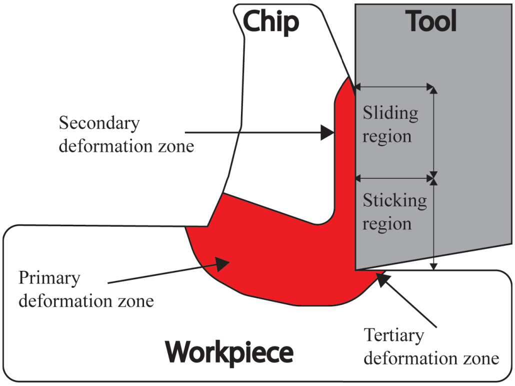


Figure 3.1: *Locations of the primary, secondary and tertiary deformation zones on the workpiece material as well sticking and sliding regions on the tool from [**2**].*

The strain distribution within this region is shown to be much greater than in the primarily zone during the chip formation [**2**]. The heat generation is mainly a cause based on the fact that the workpiece material adheres to the cutting tool during chip formation and hence, an increased friction heat. Consequently, this extreme heat generation could affect the cutting tool and the performance in machining operations [**16**]. However, in the current thesis the cutting tool will not be considered. As material is removed from the workpiece new surfaces are generated thus, the general cause for the deformation in the tertiary zone is due to the sliding action of the cutting tool edge over this surfaces. This behavior has a large influences on the surface properties of the material.
The focus of the research regarding machining, in general, concern the understanding of the complex phenomena that occur, primarily, the development of both numerical and analytical models to represent the material behavior during the process. The analytical models, in the early stage of the development, described basic mechanics behind metal cutting by the means of simplified assumptions and mathematical relationships e.g. models by Merchand [**17**] and Oxley [**18**]. As the finite element method (FEM) was introduced and the computer based simulations gained interest during the 1970s more reliable and accurate models were developed [**19**]. However, only recently, with the advent of high-speed computers on the one hand and robust large deformation procedures, contact algorithms as well fairly accurate constitutive models, have machining simulations become

possible in large extent [**3**], [**4**], [**15**], [**20**]. This could be obtained for both 2D and 3D models, accurately simulating the machining response with respect to cutting forces, temperatures, material flow and chip shape and last but not least the residual stresses on the machined surface. Nevertheless, there still exist major difficulties in simulating the machining process such as [**21**]

- Limitations regarding relevant constitutive models to accurately represent the visco-plastic material response
- Limitations concerning the contact and friction conditions between the workpiece material and cutting tool
- Lack of relevant damage criteria for describing the damage evolution in the workpiece material subjected to severe strains, strain- rates and temperatures

Consequently, the need for reliable constitutive models to describe the visco-plastic response of the workpiece material during high strains, strain rates and temperatures is of great importance. In addition the material degradation needs to be accurately evaluated and hence, representative damage and fracture criteria has to be integrated within the constitutive framework. In this thesis the third issue has been considered especially in **PAPER A**.

## 3.1 Constitutive modeling

As mentioned in the previous section one of the challenges in the FE- modeling of machining is the viability of the applied constitutive model to represent the visco-plastic material response for a wide range of strains, strain-rates and temperatures [**21**], [**22**]. As material is removed from the workpiece, forming chips, damage and fracture criteria are of great importance to accurately represent the material degradation in the vicinity of the cutting tool. Numerous constitutive models have been proposed during the years e.g. visco-plastic material model proposed by Oxley's et al. [**23**]. An additional model is the the Johnson-Cook (JC) material/constitutive model [**24**] which is often combined with the JC- fracture model [**25**] to represent the material response and degradation. As for this thesis the JC- constitutive and fracture model will be be addressed.

## 3.2 Johnson-Cook constitutive and fracture model

The JC- constitutive and fracture models are the most addressed when it comes to material representation during machining simulations and often applied in commercial softwares due to its simplicity and robustness. In the constitutive model it is assumed that the flow stress is a unique function of the total strain, the plastic strain rate and temperature as in Equation 3.1.

$$\sigma(\epsilon, \dot{\epsilon}^p, T) = \left[\sigma_y + B\epsilon^n\right]\left[1 + Cln\left(\frac{\dot{\epsilon}^p}{\dot{\epsilon}_0}\right)\right]\left[1 - \left(\frac{T - T_0}{T_m - T_0}\right)^m\right] \tag{3.1}$$

The material parameters $\sigma_y$, B and C represent initial yield at room temperature, hardening and strain rate sensitivity respectively. The equivalent plastic and reference strain rates are represented by $\dot{\epsilon}^p$ and $\dot{\epsilon_0}$, the current, melting and reference temperatures are represented by $T$, $T_m$ and $T_0$ respectively. Finally, $m$ and $n$ are the thermal softening and strain-rate hardening exponent. A disadvantage with the constitutive model is that it neglects the coupling effect between the strain, strain-rate and temperature [**1**]. Hence, modified versions have been suggested by Calamaz et al. [**26**], [**27**] and Sima and Özel [**28**] to include multiplicative dependence for the strain and temperature. However, in this thesis only the original version of the JC-constitutive model is considered.
In order to model the ductile fracture related to machining simulations the JC- fracture model is utilized. It relates the plastic fracture strain $\epsilon_f^p$ to the material triaxiality, plastic strain rate and thermal softening as in Equation 3.2

$$\epsilon_f^p(r, \dot{\epsilon}^p, T) = \left[d_1 + d_2 \exp(d_3 r)\right]\left[1 + d_4 ln\left(\frac{\dot{\epsilon}^p}{\dot{\epsilon_0}}\right)\right]\left[1 + d_5\left(\frac{T - T_0}{T_m - T_0}\right)\right] \tag{3.2}$$

where $r = \frac{\hat{p}}{\hat{\tau_e}}$ and $\hat{p}$ is the hydrostatic pressure and $\hat{\tau_e}$ is the effective von Mises stress. Here $r$ accounts for the material ductility as induced by the triaxiality of the stress state due to the void nucleation, growth and coalescence. The additional model parameters correspond to $d_1$ which is the initial failure strain, $d_2 - d_3$ refers to the triaxiality parameters while $d_4$ and $d_5$ are the strain rate and temperature parameters respectively. Note that in this thesis the temperature dependence is not utilized in the presented models.
However, up to this point the necessary models have been presented describing the fundamental material response. In order to formulate a damage criterion that signals for material degradation the damage variable $D$ is introduced as

$$D = \sum \frac{\Delta \epsilon^p}{\epsilon_f^p} = 1 \tag{3.3}$$

The material response e.g. the flow stress and other state variables are dependent on the damage evolution. This degradation could be applied in a coupled (progressive) or uncoupled (instantaneous) fashion. The later refers to the traditional "element removal" model for which the stress response is instantaneously relaxed when the damage criterion in Equation 3.3 is signaled. Figure 3.2a illustrates the material response when the traditional "element removal" model is applied for the shearing of a pearlitic plane strain plate which will be investigated firmly in **PAPER A** and **PAPER B** with respect to mesh dependence. This is a clear illustration of the inherent pathological mesh dependence that local continuum damage models such as the JC- fracture model exhibit. This corresponds to the lack of convergence of the fracture energy dissipation as discussed in [**29**]. The amount of energy released depends strictly on the corresponding element size of the mesh. Meanwhile, when the softening starts in a integration point, the deformation tends to localise while the damage evolution is concentrated to that specific point.

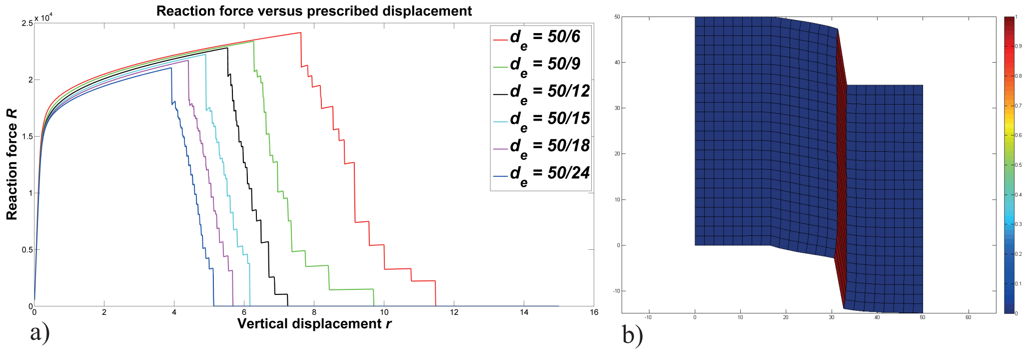


Figure 3.2: *a) The reaction force vs displacement response for different mesh sizes when utilizing the traditional "element removal" model where the influence of strain rate and temperature are disregarded. b) Localized damage distribution for element size* $d_e = \frac{50}{24}mm$

Eventually, this lead to the situation where the damage becomes localised along a specific element row as the case in Figure 3.2b which is directly coupled to the element size of the mesh. As illustrated in Figure 3.2a the material response reflects an increased brittle behavior when the element size is refined.

# 4 Mesh objective enhancement

In order to overcome the difficulties concerning the pathological mesh dependence various techniques have been developed during the years. An often applied approach is to utilise non-local damage models where the constitutive response is dependent of its neighbourhood via the introduction of non-local state variables e.g. effective plastic strain [**8**]. Additional possibilities are to augment the conventional continuum theory by discontinuous kinematics, which often result in cohesive zone modeling of the fracture process. Yet another approach to avoid the pathological mesh dependence is via the introduction of continuum damage gradient theory, e.g. Peerlings-Geers [**30**] and Mediavilla et al. [**31**] relating to the machining operations. However, recently the concepts of scalar damage phase field, based on diffuse fracture modeling, have gained interest e.g. [**9**], [**10**], [**32**]. Relating the local continuum damage theory with principles of maximum dissipation, placed in context with concepts from the phase field modeling, two significantly different mesh objective damage models are derived in **PAPER A**. For these derivation the assumption of localised damage field is utilised and hence, the continuum dissipation due to the damage evolution is therefore incorporated in the phase field context through the $\gamma$-field, defining the diffuse fracture area illustrated in Figure 4.1.

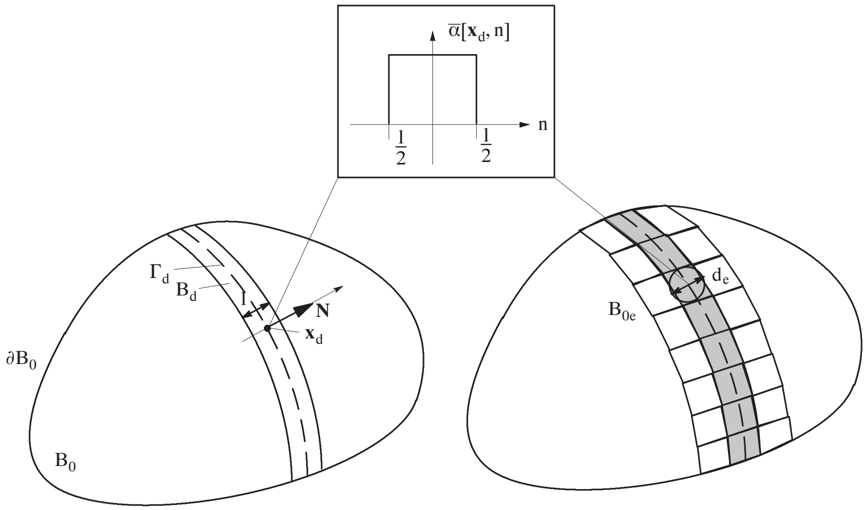


Figure 4.1: *Left picture: A solid $B_0$ with assumed localized distribution of the damage field $\alpha[x] = \bar{\alpha}[\mathbf{X_d}]$ along damage fracture surface $\Gamma_d$. Middle picture: An ideal stepwise shape of $\bar{\alpha}$ is assumed within the damage zone $B_{0d}$. Right picture: Corresponding finite element discretized solid, where the element diameter $d_e$ determines the width $l$ of the localised zone.*

The damage models were implemented in a quasi-static large deformation context excluding strain-rate and temperature dependence in **PAPER A** where it was concluded that the pathological mesh dependence was removed for both models. However, it has been argued in literature [**29**], [**33**] that incorporating visco-plastic response in the constitutive model is a potential solution to the mesh dependence. The strain-rate in a integration point will increase as it starts to gradually soften whereby the visco-plasticity in the constitutive model will prevent the damage evolution, making the element stiffer. Therefore, in **PAPER B** the presented models in **PAPER A** are enhanced with visco-plastic response in the JC-constitutive model in order to investigate the assertion.

# 5 Summary of appended papers

## 5.1 Paper A: Mesh objective continuum damage models for ductile fracture

The pathological mesh dependence concerning the JC- fracture model is investigated and a remedy to remove this behavior is proposed using two significantly different damage models. The first model, referred to as the progressive damage model in **PAPER A**, couples the damage evolution to the continuum stress response during the fracture process reflecting a smooth stress degradation. Regarding the second model, which is nothing else than the traditional "element removal" model, the damage is uncoupled from the stress response whereby an instantaneous stress relaxation is obtained when damage is signaled. In order to secure that the same amount of fracture energy is released upon mesh refinement and mesh coarsening the damage models are augmented by a mesh objective enhancement. The key feature in the development is the introduction of the damage driven force $A_T$, relating the dissipation due to the continuously deforming material and the fracture process. In order to arrive at a mesh objective formulations, the local continuum framework is combined with concepts from the phase-field modeling.

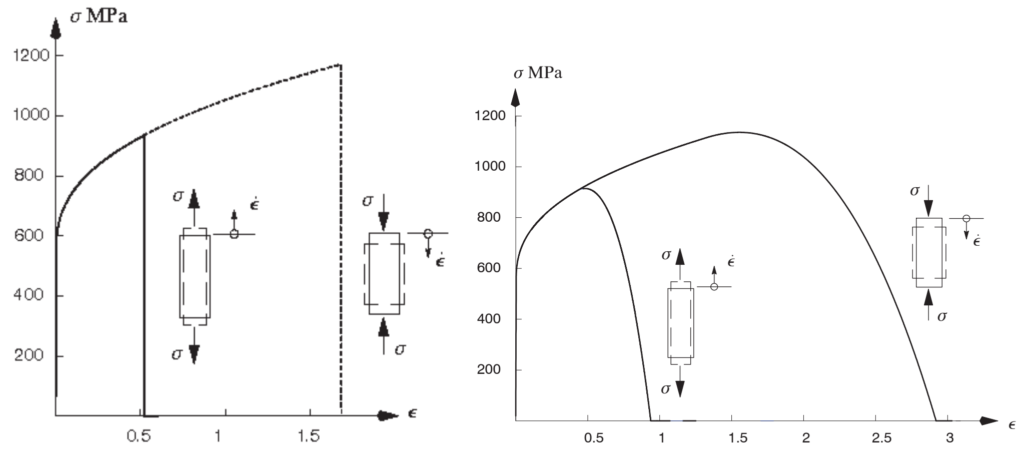


Figure 5.1: *Stress response in uniaxial compression and tension for the two considered damage models using the traditional JC- fracture model and a single element with one Gauss-Point, a) element removal model, b) progressive damage model.*

For both damage models a "fracture state" is obtained when the JC-failure criterion in Equation 3.3 is achieved. This indicates that the fracture process has initiated meanwhile the evolution of the damage is controlled by an additional damage function. The procedure is firmly discussed in **PAPER A**. However the material response for respective damage model, using a single element with one gauss-point, during uniaxial compression and tension is illustrated in Figure 5.1. A plane strain pearlitic plate, with a structured mesh, subjected to severe shear deformation was utilised in order to investigate the mesh dependence present based on force-displacement curves. The results indicate that the pathological mesh dependence was removed for finer mesh sizes than the reference mesh size when the mesh objective damage element removal model was applied. Meanwhile, utilising the mesh objective progressive damage model results in a complete removal of the mesh dependence for both coarser and finer mesh sizes than the reference mesh size. Furthermore, our simulations show that the damage tends to localise along a vertical element row as illustrated in Figure 3.2b independent of chosen damage model. The influence of unstructured mesh distribution was also investigated based on a hat specimen in [**34**]. The models are able to capture representative damage modes, and also quantitatively, a good agreement is obtained for the effective stresses and plastic strain levels. Noteworthy is the fact that the damage path becomes smeared out instead of concentrated along an element row and hence, the lack of clear convergence in the force vs displacement curves. In this contribution strain-rate and temperature dependence were excluded for the numerical simulations conducted.

## 5.2 Paper B: Mesh objective modeling of ductile fracture at visco-plastic continuum response

The models derived in **PAPER A** are extended incorporating visco-plastic material response in the JC- constitutive model and implemented in ABAQUS/Explicit as a user subroutine. The assertion postulated in the literature regarding that viscous regularization of the continuum material model coupled to damage via visco-plasticity may remove the mesh dependence is investigated when the objective enhancement is excluded from the damage models. This investigation was initially conducted for the same plane strain pearlitic plate subjected to severe shear deformation as in **PAPER A** using different displacement rates. Additionally, the perforation of a Weldox 460 E steel plate by a blunt-nosed projectile [**35**] is considered in the current paper. The penetration describes similar conditions that occur during machining operations whereby, it provides beneficial information regarding the damage models ability to represent the material behavior under such conditions. Our results regarding the initial numerical example indicate that the pathological mesh dependence was not removed when a visco-plastic material model was utilized. However, with the introduction of the objective enhancement the mesh dependence was minimized for both damage models. Unfortunately, a overestimation of the force-displacement behavior for the finest mesh sizes with respect to the reference mesh size was obtained. Independent of damage model or whetter the objective enhancement is used or not, dynamic effects were present in the force-displacement curves, appearing as vibrations. A possible approach to minimize or completely damp these out was by the introduction of mass proportional damping. As for the perforation of the Weldox 460 E steel plate, we are able confirm both with respect to field experiments and numerical simulations in [**35**] that our proposed damage models, despite lack of temperature dependence, are able to qualitatively describe the process. The residual velocities for the projectile and plug, the fracture patterns and the plastic strain distribution in the plate are captured for a initial projectile velocity well above the ballistic limit velocity, when excluding objective enhancement in the models. However, assuming that the ballistic limit velocity for our models is equal to the one in [**35**] is shown to be incorrect. This is due to the fact that no penetration through the plate is obtained if a initial projectile velocity slightly above the provided ballistic limit velocity in literature is used. Therefore, by curve fitting the Retch-Ipson model based on numerical simulations with varying initial projectile velocity we were able to show that the primary reason for this response was due to an increase of the ballistic limit velocity in our models.

# 6 Conclusions and future work

## Conclusions

To optimize the manufacturing processes a reliable representation of the material response during the machining operations is crucial. This is preferably addressed by simulating the specific operations by means of the finite element method. For this purpose, the utilisation of credible constitutive and damage models to intercept the complex phenomena occurring in the vicinity of the cutting tool edge is of great importance. Consequently, the well established empirical JC-constitutive and fracture models are applied for the representation of the material response in the current work.
The primary focus in this thesis concerns the damage modeling, with the emphasis on the restriction of local continuum damage models concerning the inherited pathological mesh dependence. Based on a local continuum damage formulation incorporated with concepts of a scalar damage phase field a remedy is proposed for the observed mesh dependence in the JC-fracture model. In this context, two mesh objective damage models are proposed in **PAPER A**, the progressive damage model for which the damage is coupled to the continuum stress response during the fracture process and the damage element removal model where the stress response is uncoupled from the damage evolution.
In **PAPER A** an investigation regarding the performance of the damage models with respect to mesh distortion was conducted. Our results, with respect to the shearing of the plane strain plate, show that both damage models are able to remove the pathological mesh size dependence using a structured mesh while excluding temperature and strain rate dependence. As for the hat specimen with an unstructured mesh our results show that realistic damage path is captured, and also quantitatively, a good agreement is obtained for the effective stress and plastic strain levels compared to literature. Furthermore, extending the constitutive model in order to incorporate visco-plasticity as in **PAPER B** still results in a pathological mesh dependence in the force-displacement curves when the mesh objective enhancement is excluded for the shearing of the plane strain plate. Meanwhile, with the introduction of the objective enhancement a better convergence is achieved, independent of displacement rate. However a shift in the force-displacement curves is obtained for the two finest mesh sizes independent of damage model when excluding the mesh objectivity.
The visco-plastic models have been validated based on the perforation of a steel plate by a blunt-nosed projectile in **PAPER B** which replicates similar conditions that occur during machining operations. We have shown that both damage models are able to accurately predict the impact process when a initial projectile velocity much higher than the ballistic limit velocity is applied. The residual velocities for the projectile and plug as well as the plastic strain distribution and fracture patterns are in accordance with both numerical and experimental results provided in [**35**]. Unfortunately the models were not able to represent the penetration that occur when a initial projectile velocity slightly higher than the ballistic limit velocity in [**35**] was utilised. The assertion in [**36**] regarding lack of pathological mesh dependence during perforation of a Weldox 460 E steel plate when a visco-plastic material model was applied has been investigated using

the progressive damage model excluding the objective enhancement. The postulation seems to be correct, no clear pathological mesh dependence is detected for the residual velocities of the projectile and the plug. However, the convergence is improved if the objective enhancement is utilised.

# Future work

Regarding further work, we remark that the JC- constitutive and fracture models are restricted to plastic strain, stress triaxiality and strain rate sensitivity only while temperature dependence is neglected. Further developments are therefore necessary to make the modelling more reliable,

- **Temperature dependence**:
  To accurately represent the material behavior and to analyse the complex phenomena occurring during machining, implementation of the temperature dependence in the JC-models is a obvious step. In addition, investigate the coupling behavior between temperature and strain rate dependence, e.g. adiabatic shear bands.

- **Parameter calibration**:
  The material parameters, primarily fracture energy, utilised in the damage models need to be calibrated based on experimental data e.g. coupling the fracture energy to fracture toughness of the considered material.

- **Adaptive meshing**:
  Investigate the possibility to take advantage of the ALE adaptive meshing technology in commercial softwares, e.g. ABAQUS/Explicit, LS-DYNA etc.

- **Simulation tool**:
  Develop a reliable simulation tool to represent machining operations e.g. turning, cutting.

  - *2D machining*
    Apply the damage models to a 2D machining simulation of e.g. orthogonal cutting.
  - *Contact conditions*
    As the contact between the workpiece material and the cutting tool is a central source of heat distribution, the need for a accurate representation of the interaction is important and should be investigated.
  - *Cutting tool representation*
    Instead of modelling the cutting tool as a rigid body, investigate the possibility to represent the tool as a deformable body in the simulation tool. This provides the possibility to analyse cutting tool wear which is vital indicator for evaluating the machinability of the workpiece material [**16**].

- **Material**:
  The main material studied so far is of pearlitic steel, other materials, steels or more

heterogeneous materials like cast iron may be considered. However, this requires knowledge/calibration of values for pertinent material parameters.

- **Validation**:
  The simulation tool needs to be further validated, this is preferably obtained based on experimental data from machining operations, e.g. turning and cutting where the process parameters, e.g. cutting force, temperature distribution, surface integrity, residual stresses etc. are exploited.

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