Seeing what the eye cannot see

Using DIC and in-situ SEM to study the micromechanics of pearlitic steel

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Full field deformation and strain measurements with a focus on optical techniques
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Contents

Introduction

Full-field measurements

- Topic of this seminar: Full field deformation and strain measurements
- How can we use full-field measurements to learn more about materials?
  - Several examples during this seminar
  - Qualitative
  - Quantitative
- Present study: use data from DIC analysis of in-situ SEM micrographs of a pearlitic steel

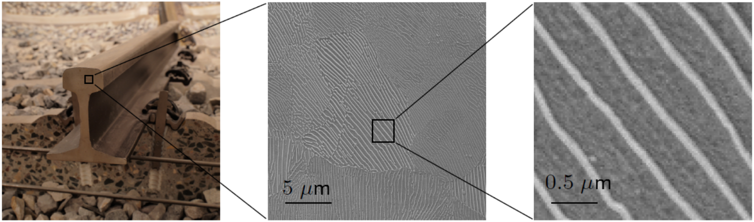
Introduction

Engineering applications

- Applications: suspension bridges, cable cars, railway applications, ...
- Severe loads during manufacturing and/or operation
- Loading $\Leftrightarrow$ Microstructure $\Leftrightarrow$ Mechanical behavior
  [Wetscher, Toribio, ...]

Introduction

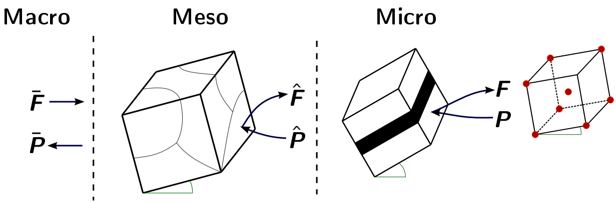
Length scales



- Macroscale
  - Homogeneous appearance
  - Initially isotropic
- Mesoscale
  - Colonies (constant lamella orientation)
  - Local anisotropy
  - Severe loads: alignment of cementite lamellae
- Microscale: cementite lamellae (brittle) embedded in ferrite (ductile)
- Next: how to include such knowledge in a constitutive model?

Multiscale modeling

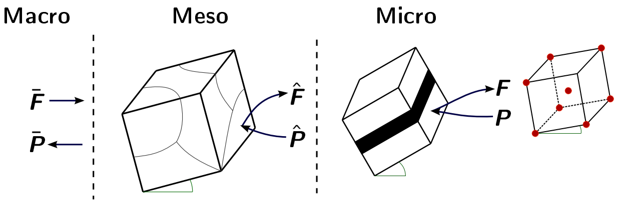
Preliminaries



- Main idea: replace macroscopic constitutive model with a Representative Volume Element (RVE) [Feyel, Miehe, Geers, Wriggers, Zodhi ...]
- Enables known subscale features and mechanisms to be included in the model
- Model calibration: macroscopic data and/or subscale data
- Computational cost
- Virtual experiments

Multiscale modeling

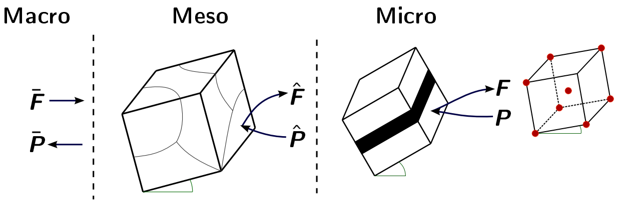
Mesoscale RVE



- Local macroscopic response obtained from homogenization of mesoscale RVE
- Aggregate of colonies
- Meso-RVE needs to include a sufficient number of colonies to be representative
- Mechanical behaviour of individual colonies
- Interactions between colonies
- Local mesoscopic response obtained from homogenization of microscale RVE

Multiscale modeling

Microscale RVE



- Models the mechanical behaviour of the two phases: cementite and ferrite
- Takes into account how they interact with each other
- Constitutive framework needed to tie things together: crystal plasticity
- Note: model parameters are defined on microscale

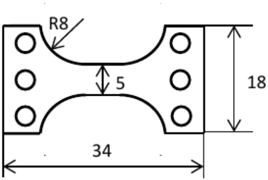
Present study

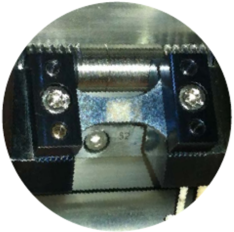
Objectives and outline

- Collaboration with:
  - Johan Ahlström (Chalmers)
  - Magnus Colliander (Chalmers/GKN)
  - Ru Peng (Linköping University)
- Analyze in-situ SEM micrographs of pearlite using DIC
- Increased understanding of microscale mechanisms
- Investigate possibilities for using microscale data for model calibration
- Microstructure used as a natural speckle
  - How to handle regions ill-posed for DIC-procedure?
- No distortion correction!

Present study

Experimental setup

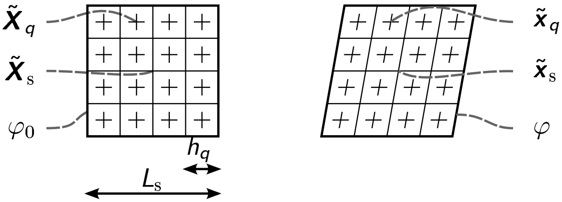




- Test material: ASTM 1080 carbon steel
- Test equipment: Hitachi SU-70 FEG- SEM with a Gatan microtest tensile stage
- Experiments carried out in cooperation with Linköping University
- Macroscopic data: applied force
- Subscale data: SEM micrographs at varying global load levels
- Micrographs to be processed using DIC

Present study

DIC - preliminaries



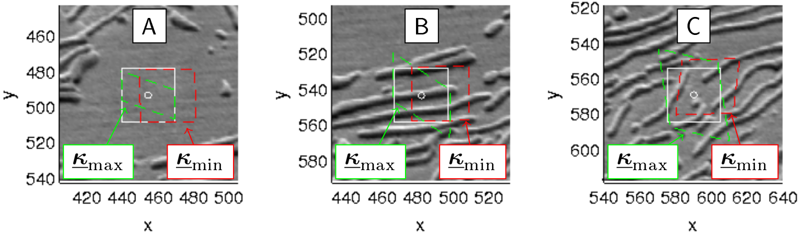
- Definition of correlation function [Sutton, Reu, Hild, Roux, Ranson, Peters, Schreier, Vendroux...]

$$c(\tilde{\boldsymbol{X}}, \underline{\boldsymbol{\kappa}}, t) = \frac{1}{N_q} \sum_{q=1}^{N_q} [\gamma_q - \gamma_{0,q}]^2 \quad (1)$$

- Subset kinematics

$$\tilde{\boldsymbol{x}}_q(\underline{\boldsymbol{\kappa}}) = \begin{cases} \tilde{\boldsymbol{X}}_q + \tilde{\boldsymbol{u}}_s & \mathrm{k} = 0 \\ \tilde{\boldsymbol{X}}_q + \tilde{\boldsymbol{u}}_s + \tilde{\boldsymbol{H}}_s \cdot [\tilde{\boldsymbol{X}}_s - \tilde{\boldsymbol{X}}_q] & \mathrm{k} = 1 \\ \ldots \end{cases} \quad (2)$$

Identification of high quality subsets

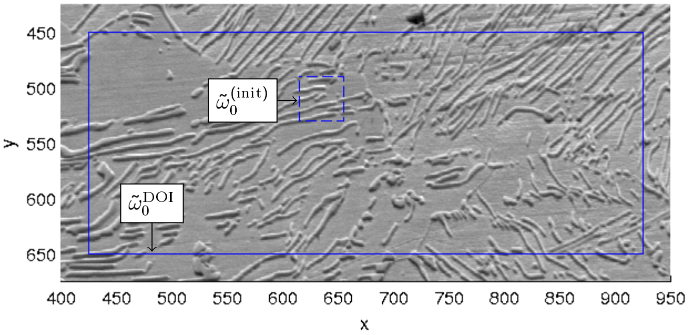


- Synthetic speckles vs. natural speckle
- Traceability indicators: initial standard deviation and eigenvalues of the Hessian of the autocorrelation function

$$\underline{\boldsymbol{K}}_{\mathrm{a}} \cdot \underline{\boldsymbol{\kappa}}^{(\mathrm{I})} = \lambda^{(\mathrm{I})} \underline{\boldsymbol{\kappa}}^{(\mathrm{I})} \text{ where } \begin{cases} \underline{\boldsymbol{K}}(\tilde{\boldsymbol{X}}, \underline{\boldsymbol{\kappa}}, t) = \frac{\partial^2 c}{\partial \underline{\boldsymbol{\kappa}} \otimes \partial \underline{\boldsymbol{\kappa}}} \\ \underline{\boldsymbol{K}}_{\mathrm{a}}(\tilde{\boldsymbol{X}}) \equiv \underline{\boldsymbol{K}}(\tilde{\boldsymbol{X}}, \underline{\boldsymbol{\kappa}} = \underline{\mathbf{0}}, t = 0) \end{cases}$$

Identification of high quality subsets

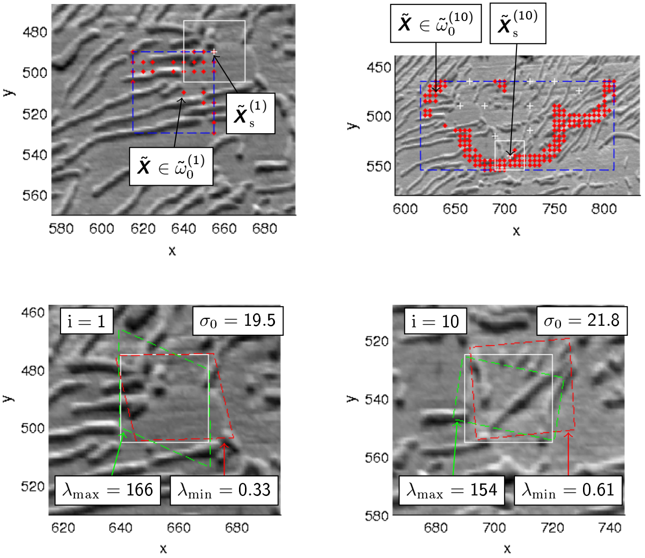
Algorithm



- Dense background grid of subsets
- Would like to cover the DOI with subsets which have a well-defined correlation functions

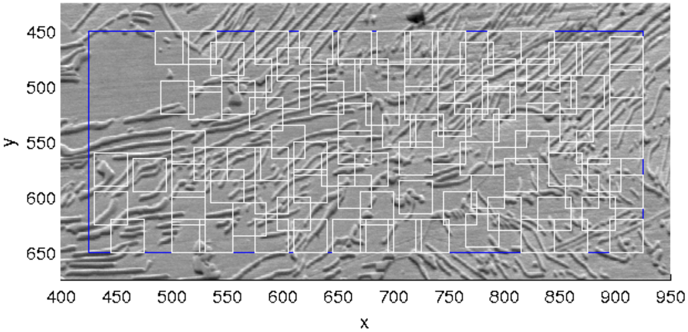
Identification of high quality subsets

Iterative procedure



Identification of high quality subsets

Identified subsets



- The domain is covered with subsets that fulfill the traceability criteria
- Domains with limited information quality are avoided

Error estimation

- A known motion is applied to an initial image

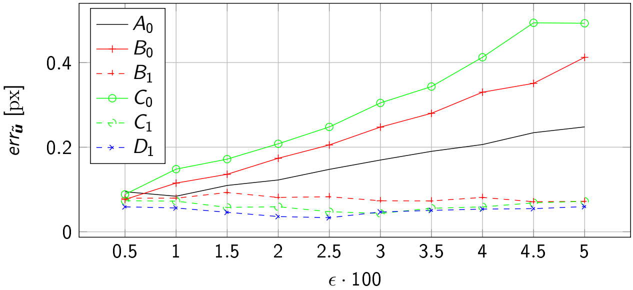
$$[\tilde{\boldsymbol{x}} - \tilde{\boldsymbol{x}}_{\mathrm{R}}] = [\tilde{\boldsymbol{H}} + \boldsymbol{I}] \cdot [\tilde{\boldsymbol{X}} - \tilde{\boldsymbol{X}}_{\mathrm{R}}]\tilde{\boldsymbol{u}} = \tilde{\boldsymbol{H}}[\tilde{\boldsymbol{X}} - \tilde{\boldsymbol{X}}_{\mathrm{R}}]$$

- Uniaxial elongation in the horizontal direction is considered
- Both displacements and the displacement gradient is known in the entire image domain
- A number of setups are evaluated

k	0	0	0	1	1	1
L_{s}	10.5	20.5	30.5	20.5	30.5	40.5
Label	A_0	B_0	C_0	B_1	C_1	D_1
N_{s}	2087	1755	755	1915	838	557

Error estimation

Local displacements



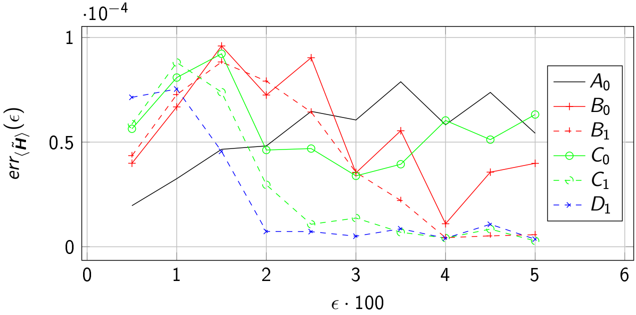
- The local displacement error is introduced:

$$err_{\tilde{\boldsymbol{u}}} = err_{\tilde{\boldsymbol{u}}}(\epsilon) = \max_{\mathrm{i}}(|\tilde{\boldsymbol{u}}(\tilde{\boldsymbol{X}}_{\mathrm{s}}^{(\mathrm{i})}, \epsilon) - \tilde{\boldsymbol{u}}_{\mathrm{s}}^{(\mathrm{i})}|)$$

- Using first order kinematics gives better results
- Subset size has little impact (k=1)

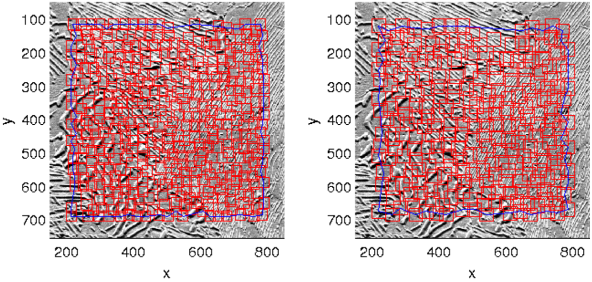
Error estimation

Average displacement gradient



- Using first order kinematics improves the results
- Using a larger subset improves the results
- Note: Constant displacement gradient in domain

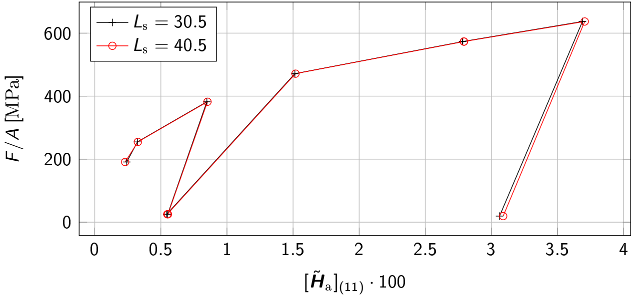
DIC analysis of in-situ SEM micrographs



- Two subset sizes are considered: $L_\mathrm{s} = 30.5$ [px] and $L_\mathrm{s} = 40.5$ [px]
- The procedure for identification of high quality subsets is used

DIC analysis of in-situ SEM micrographs

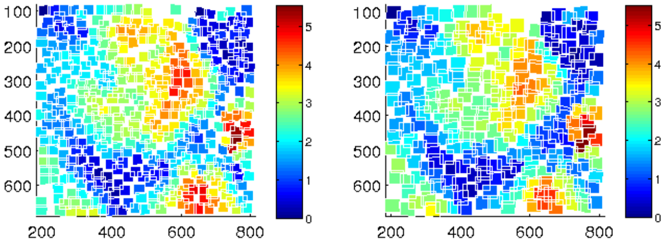
Identified strain history



- Results are rather insensitive to the chosen subset size (robustness)
- Note: reloading path not resolved

DIC analysis of in-situ SEM micrographs

Fluctuation field



- Impact of material morphology and crystallographic orientations can be visualized using the fluctuation fields
- The two analyses give qualitatively similar results
- Grain like domains can be identified (compare with EBSD maps)

Concluding remarks

- In-situ obtained SEM images have been analyzed using Digital Image Correlation
- The microstructure of the material is used as a natural speckle
- A method for identification of high-quality subsets within a DOI is proposed
- The implementation of the DIC framework is validated using synthetically deformed images
- The method is robust (insensitive to the chosen subset size) when it comes to identifying displacements and the average displacement gradient
- Future work
  - Influence from sub-surface morphology (tomography+DVC)?
  - Compensate for SEM image distortion
  - FE-DIC
  - Parameter value identification (FEMU, VFM, ...)
- Acknowledgement:
  - Linköping University
  - Swedish Reasearch Council
  - The Areas of Advance in Materials Science and Transport,

Concluding remarks

Questions?