

Modeling of a Single Pulse Electric Discharge at Sphere/flat Interface by Coupling Contact Multiphysics and Phase Transformations

Presented at the COMSOL Conference 2010 Paris

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Giovanni Maizza
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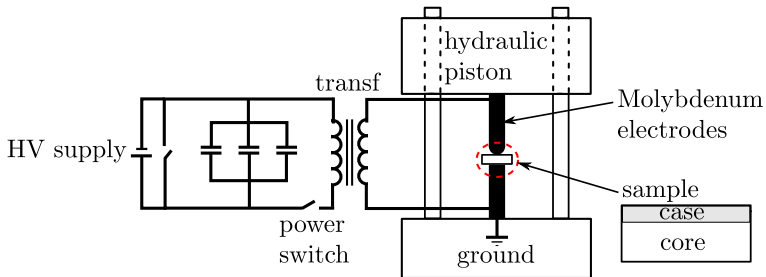


Politecnico di Torino
Department of Materials Science and Chemical Engineering

November 15, 2010

The apparatus

Capacitor Discharge Welding



Short processing times + high localized energy density

Applications: welding of metals, ceramics, composites

Modules and features

- Elasto-plastic solver
- DC-electrical module
- Thermal module
- Contact pair features
- Solid state transformations by user-defined functions
- Materials properties definition dependent on temperature and phase content in steel

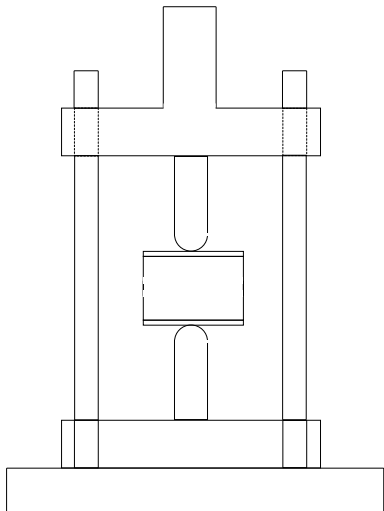


Version 3.5a

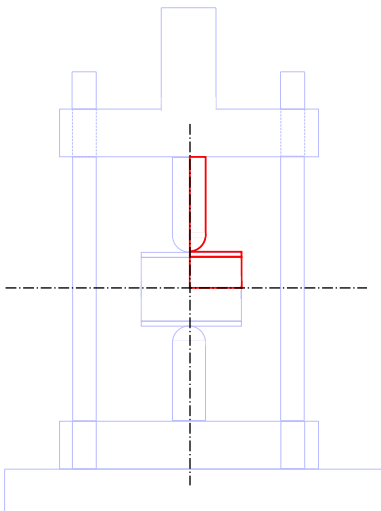
Outline

- 1 Model implementation
 - Domain
 - Structural-mechanical
 - Electrical
 - Thermal
 - Phase transformation
 - Solution strategy
- 2 Results
 - Structural
 - Thermal
 - Phase transformation
- 3 Conclusions

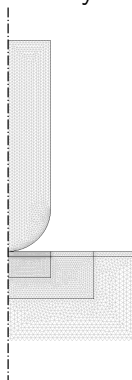
Model implementation – Domain



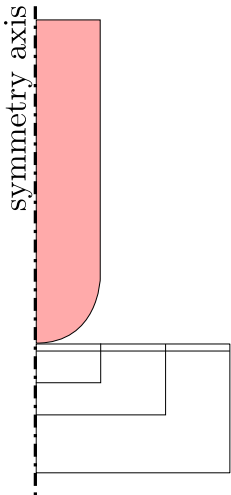
Model implementation – Domain



Axial symmetry, 2D



Model implementation – Domain



Electrode

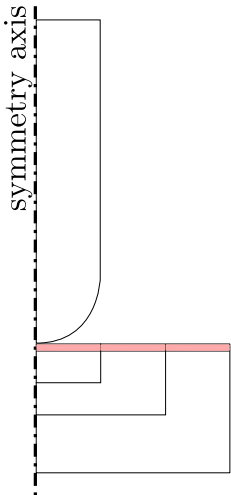
Molybdenum

Height: 25 mm

Diameter: 10 mm

Spherical shaped tip

Model implementation – Domain



Sample case

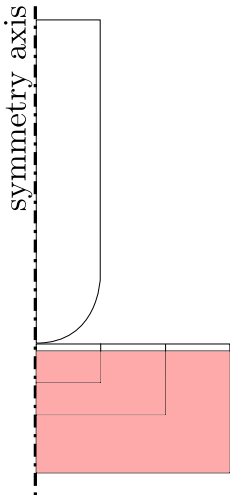
AISI 9310 steel

case hardened

Height: 0.6 mm

Diameter: 30 mm

Model implementation – Domain



Sample core

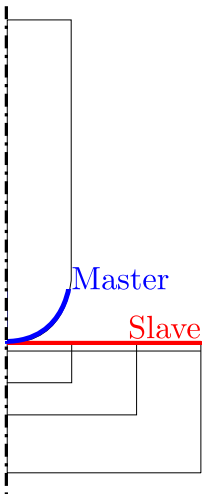
AISI 9310 steel

annealed

Height: 9.4 mm

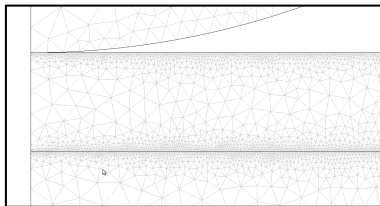
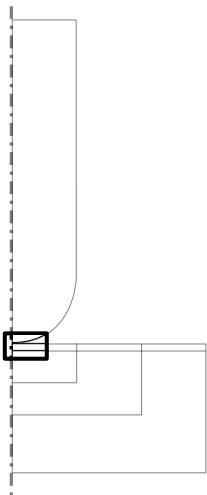
Diameter: 30 mm

Model implementation – Domain



Contact pair

Model implementation – Domain



Mesh data

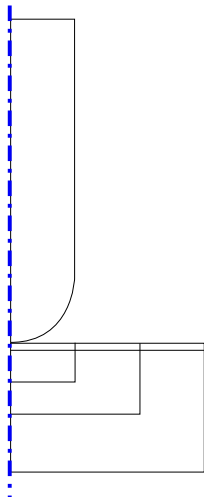
Quadratic lagrangian elements
Triangular (advancing front)

Model implementation

STATIONARY STRUCTURAL-MECHANICAL

- Elasto-plastic behavior of sample, electrode and contact region
- Isotropic tangent modulus E_{Tiso}

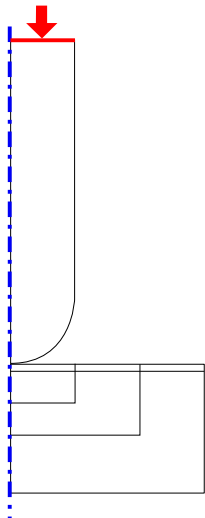
Model implementation – Structural



Boundary conditions

- Axial symmetry

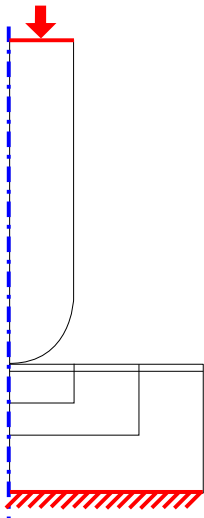
Model implementation – Structural



Boundary conditions

- Axial symmetry
- Applied pressure: 35 MPa

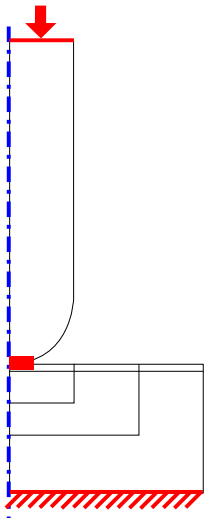
Model implementation – Structural



Boundary conditions

- Axial symmetry
- Applied pressure: 35 MPa
- Fixed edge of the sample

Model implementation – Structural

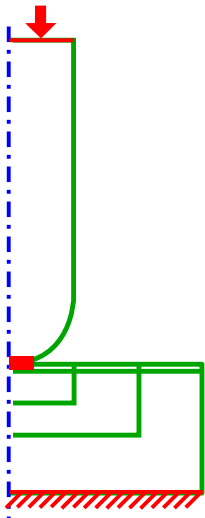


Boundary conditions

- Axial symmetry
- Applied pressure: 35 MPa
- Fixed edge of the sample
- Penalty factor:

$$P_n = \frac{E_{smaxi}}{hmin_{cp1} smaxi} \cdot \min(1.e^{-3} \cdot 5^{aug}, 1)$$
- Initial contact pressure: 10 MPa

Model implementation – Structural



Boundary conditions

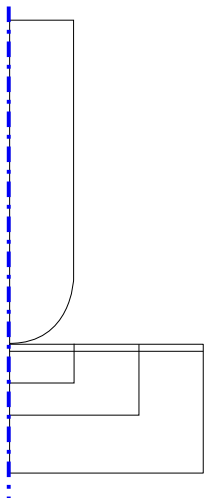
- Axial symmetry
- Applied pressure: 35 MPa
- Fixed edge of the sample
- Penalty factor:

$$P_n = \frac{E_{smaxi}}{hmin_{cp1} smaxi} \cdot \min(1.e^{-3} \cdot 5^{aug}, 1)$$
- Initial contact pressure: 10 MPa
- Free displacement for the rest

Model implementation

STATIONARY ELECTRICAL

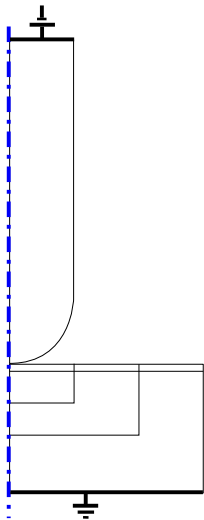
Model implementation – Electrical



Boundary conditions

- Axial symmetry

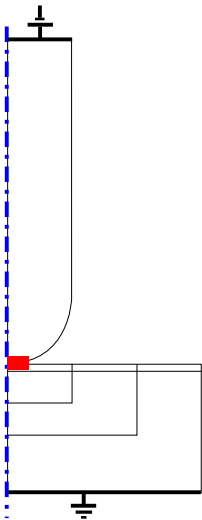
Model implementation – Electrical



Boundary conditions

- Axial symmetry
- Voltage drop ΔV^*

Model implementation – Electrical



Boundary conditions

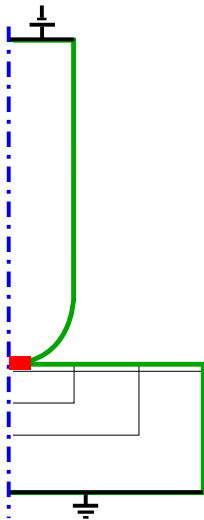
- Axial symmetry
- Voltage drop ΔV^*
- Contact resistance

$$\sigma_c = \frac{\rho_{e1} + \rho_{e2}}{4r_c} \quad [1]$$

$$r_c = \text{contact radius}$$

[1] R. Holm, Electrical Contacts, Hugo Gebers, Stockholm, (1936)

Model implementation – Electrical



Boundary conditions

- Axial symmetry
- Voltage drop ΔV^*
- Contact resistance

$$\sigma_c = \frac{\rho_{e1} + \rho_{e2}}{4r_c} \quad [1]$$

$$r_c = \text{contact radius}$$

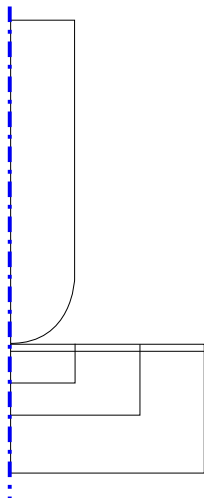
- Electric insulation

[1] R. Holm, Electrical Contacts, Hugo Gebers, Stockholm, (1936)

Model implementation – Thermal

TRANSIENT THERMAL

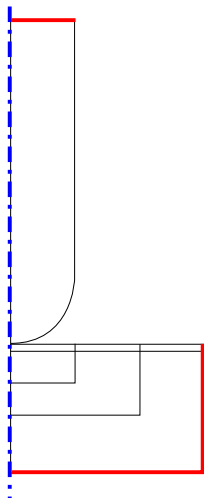
Model implementation – Thermal



Boundary conditions

- Axial symmetry

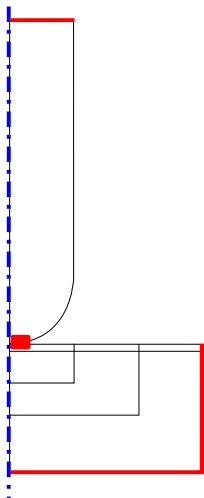
Model implementation – Thermal



Boundary conditions

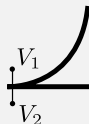
- Axial symmetry
- Fixed temperature (massive copper tooling)

Model implementation – Thermal



Boundary conditions

- Axial symmetry
- Fixed temperature (massive copper tooling)
- Joule heating: $\dot{Q}_T = \frac{\sigma_c}{d} (V_1 - V_2)$

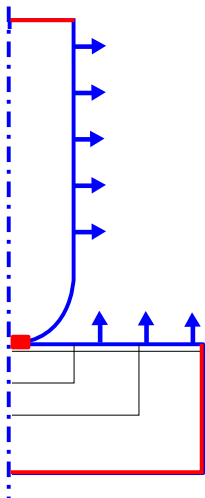


$$\sigma_c = \frac{\rho_{e1} + \rho_{e2}}{4r_c} [1]$$

r_c = contact radius

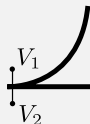
[1] R. Holm, Electrical Contacts, Hugo Gebers, Stockholm, (1936)

Model implementation – Thermal



Boundary conditions

- Axial symmetry
- Fixed temperature (massive copper tooling)
- Joule heating: $\dot{Q}_T = \frac{\sigma_c}{d} (V_1 - V_2)$



$$\sigma_c = \frac{\rho_{e1} + \rho_{e2}}{4r_c} [1]$$

r_c = contact radius

- Heat flux: $h = 50 \text{ W}/(\text{K m}^2)$

[1] R. Holm, Electrical Contacts, Hugo Gebers, Stockholm, (1936)

Model implementation

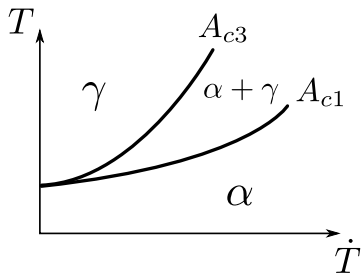
PHASE TRANSFORMATION and INERTIAL EFFECTS

Assumptions:

- high temperature cycling
- high heating rates
- rapid reaustenitization
- narrow heat affected zone

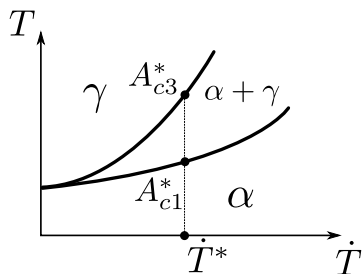
Inertial effects without growth kinetics modeling

Model implementation – Phase transformation



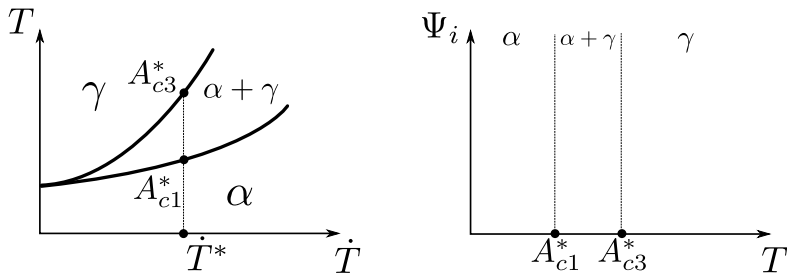
- A_{c1} and A_{c3} curves from experimental data

Model implementation – Phase transformation



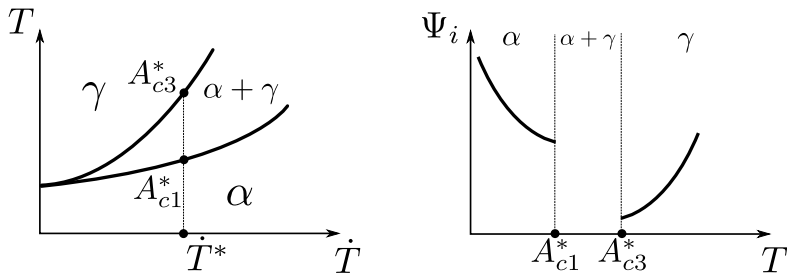
- A_{c1} and A_{c3} curves from experimental data
- \dot{T} defines univocally the phase fields

Model implementation – Phase transformation



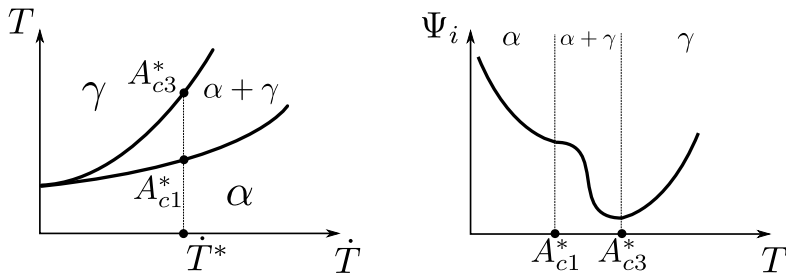
- A_{c1} and A_{c3} curves from experimental data
- \dot{T} defines univocally the phase fields
- Ψ_i represents a general material property

Model implementation – Phase transformation



- A_{c1} and A_{c3} curves from experimental data
- \dot{T} defines univocally the phase fields
- Ψ_i represents a general material property
- Properties values in pure α and pure γ phase from experimental data

Model implementation – Phase transformation



- A_{c1} and A_{c3} curves from experimental data
- \dot{T} defines univocally the phase fields
- Ψ_i represents a general material property
- Properties values in pure α and pure γ phase from experimental data
- Properties values in two-phase region obtained by sigmoidal function `flc1hs`

Model implementation

SOLUTION STRATEGY

Model implementation – Solution strategy

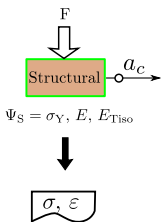
$\Psi_i(T, \text{phase}) = \text{general material property where } i = E, T, S$

E = Electrical

T = Thermal

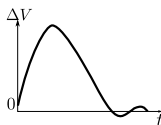
S = Structural

pre-loading

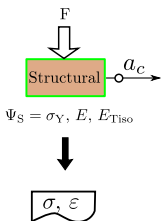


Model implementation – Solution strategy

DC pulse discharge curve

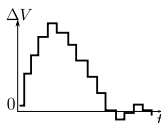


pre-loading

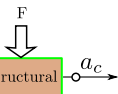


Model implementation – Solution strategy

DC pulse discharge curve



pre-loading



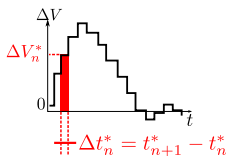
$$\Psi_S = \sigma_Y, E, E_{Tiso}$$



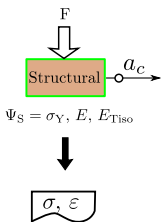
σ, ε

Model implementation – Solution strategy

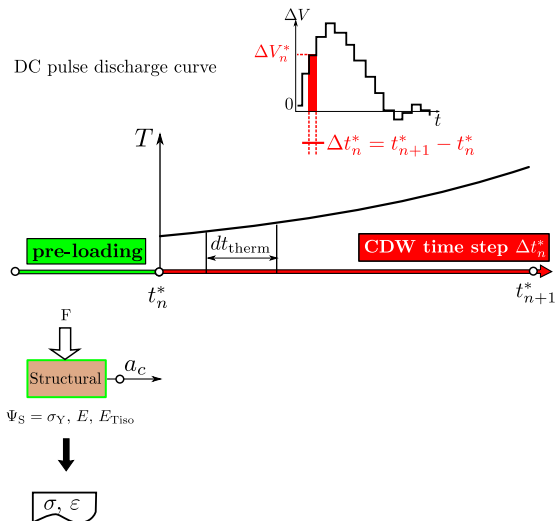
DC pulse discharge curve



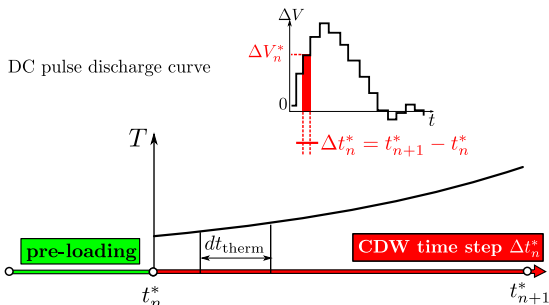
pre-loading



Model implementation – Solution strategy

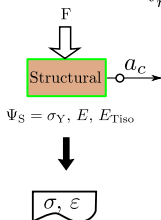


Model implementation – Solution strategy

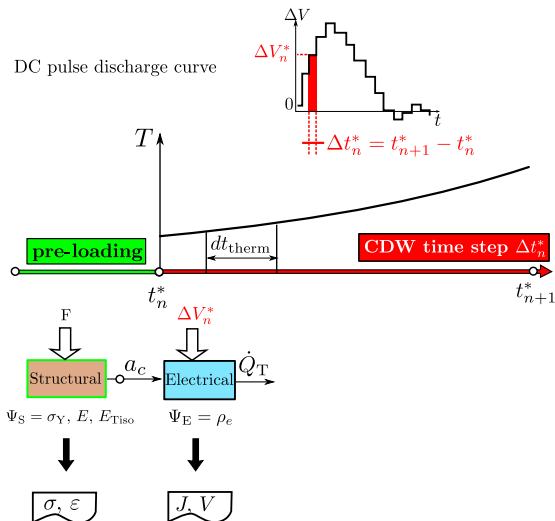


Two assumptions:

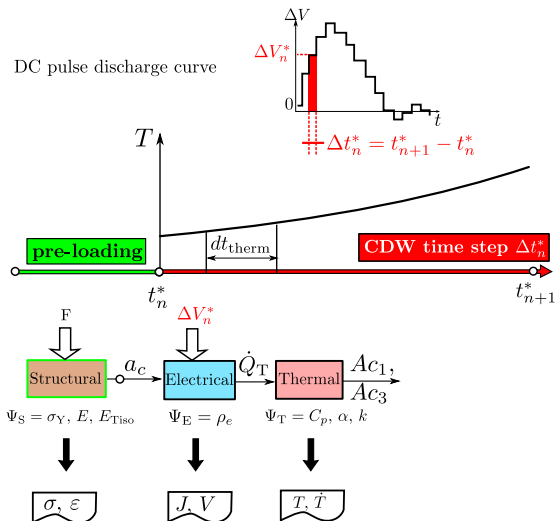
1. CDW phenomena are driven by thermal field
2. Electrical phenomenon time constant of the same order of magnitude of the thermal phenomenon



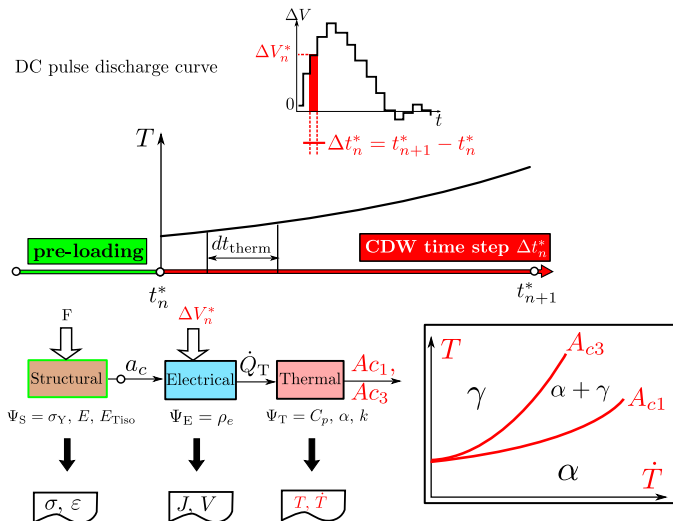
Model implementation – Solution strategy



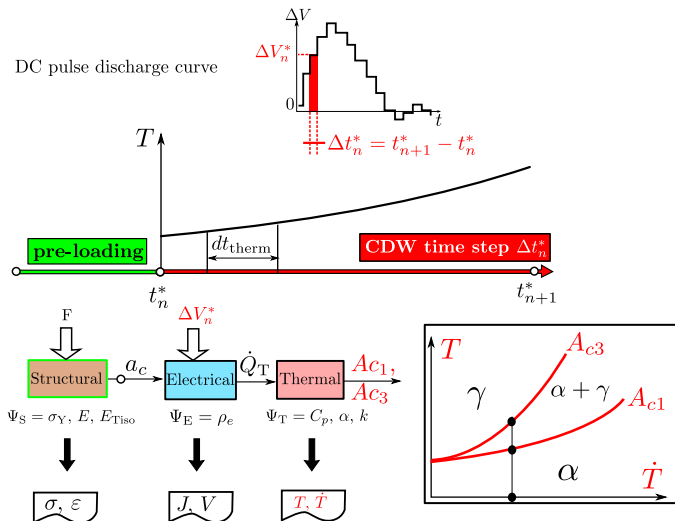
Model implementation – Solution strategy



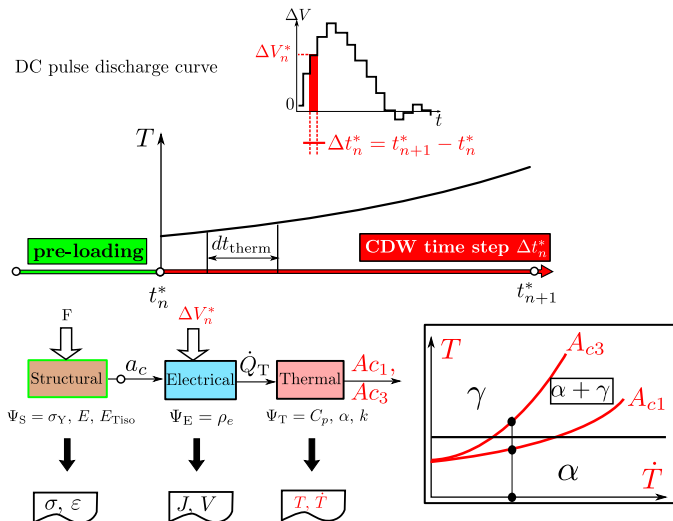
Model implementation – Solution strategy



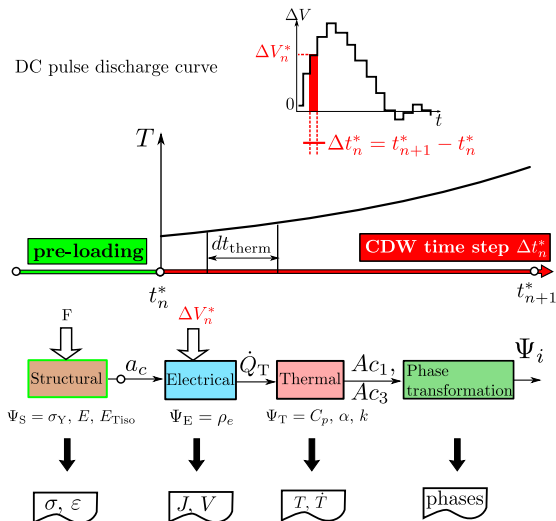
Model implementation – Solution strategy



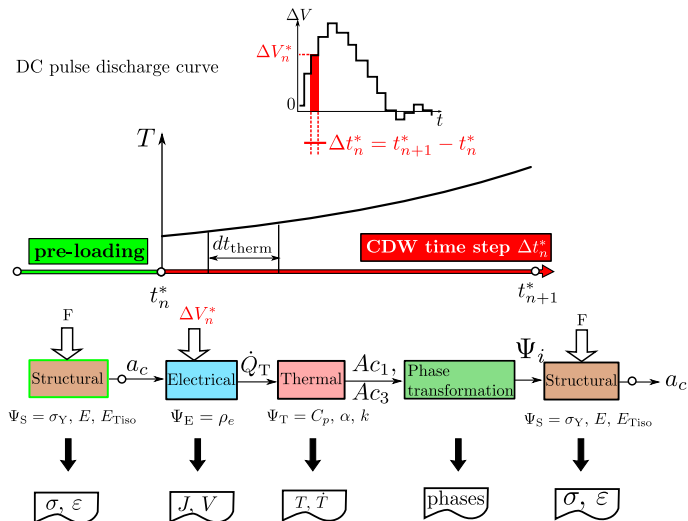
Model implementation – Solution strategy



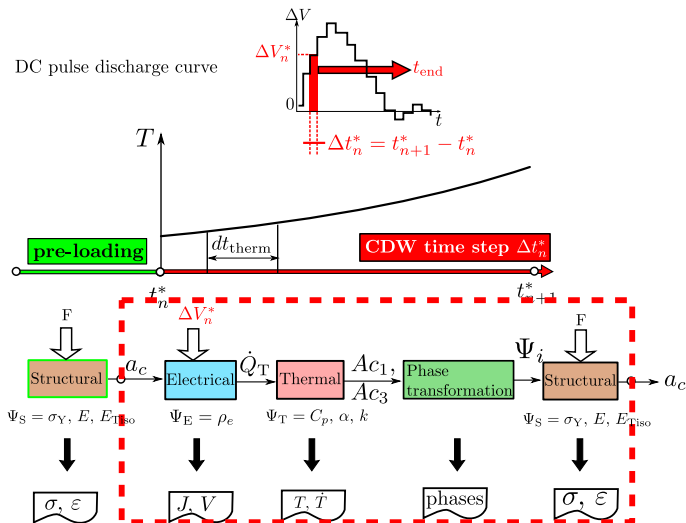
Model implementation – Solution strategy



Model implementation – Solution strategy



Model implementation – Solution strategy



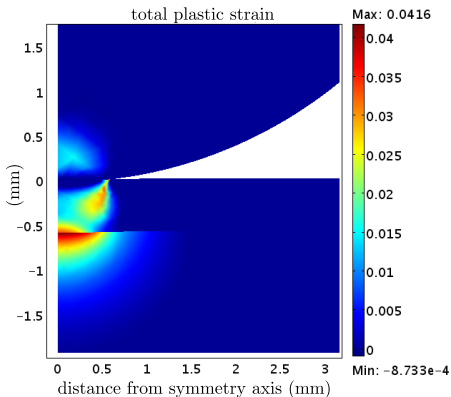
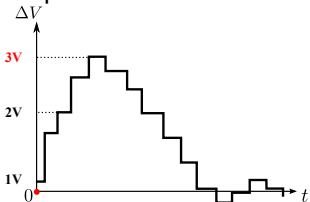
Results

- Structural
- Thermal
- Phase transformation

Results – Structural

Pre-loading

No Applied voltage
Elapsed time: 0 ms

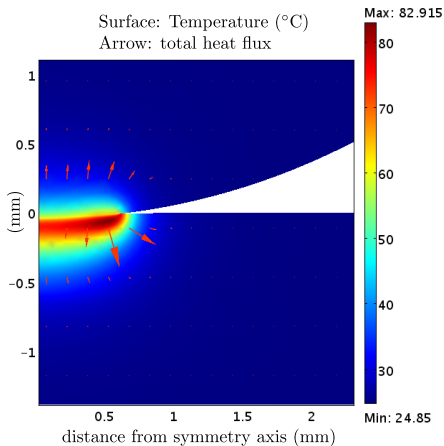
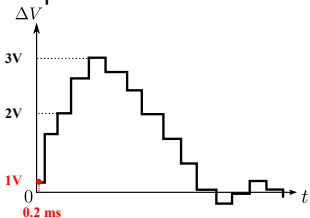


Results – Thermal

CDW step:

Applied voltage ΔV^* : 1 V

Elapsed time: 0.2 ms

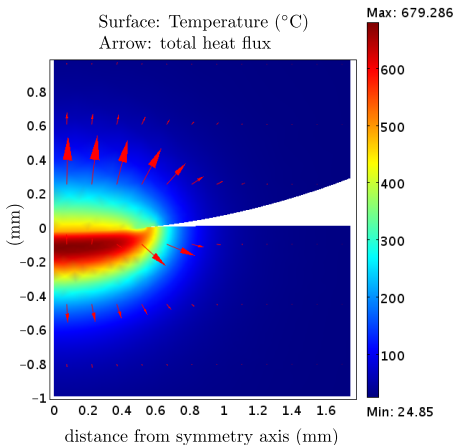
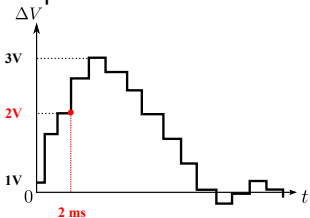


Results – Thermal

CDW step:

Applied voltage ΔV^* : 2V

Elapsed time: 2.0 ms

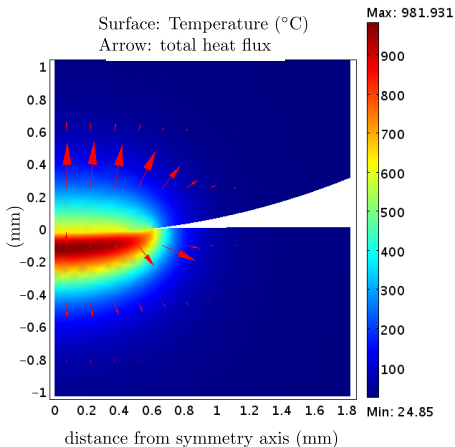
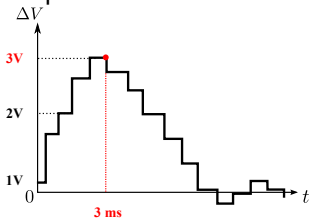


Results – Thermal

CDW step:

Applied voltage ΔV^* : 3 V

Elapsed time: 3.0 ms

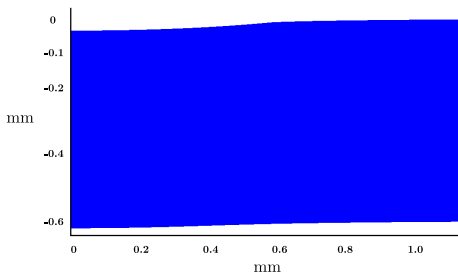
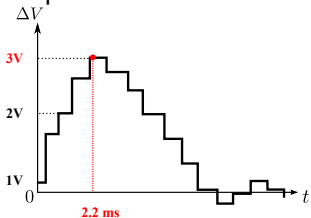


Results – Phase transformation

CDW step: focus on sample case

Applied voltage ΔV^* : 3V

Elapsed time: 2.2 ms



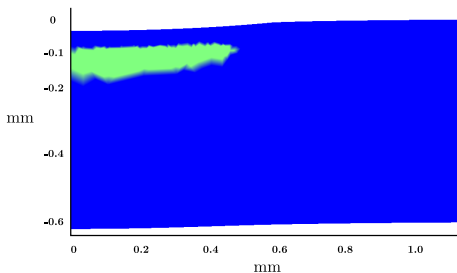
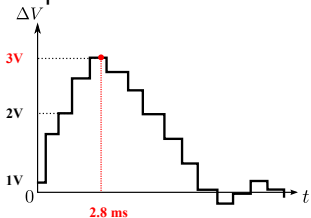
- Martensite
- Martensite+austenite
- Austenite

Results – Phase transformation

CDW step: focus on sample case

Applied voltage ΔV^* : 3V

Elapsed time: 2.8 ms



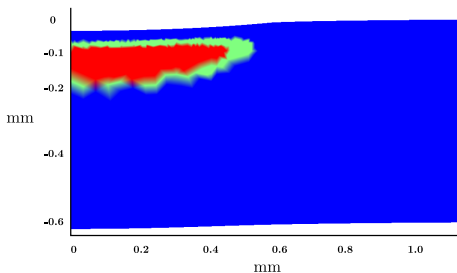
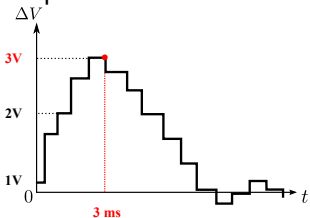
- Martensite
- Martensite+austenite
- Austenite

Results – Phase transformation

CDW step: focus on sample case

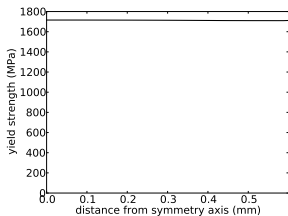
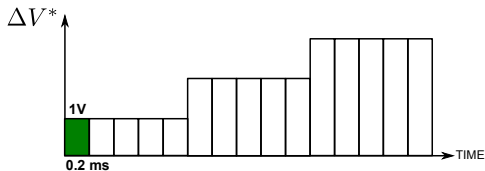
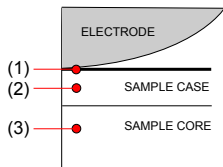
Applied voltage ΔV^* : 3V

Elapsed time: 3.0 ms

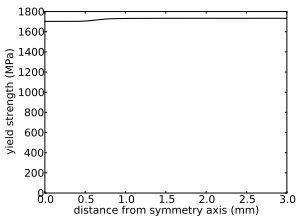


- Martensite
- Martensite+austenite
- Austenite

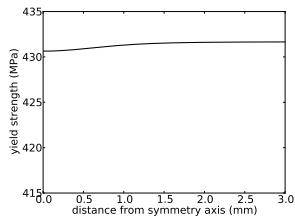
Results – Yield strength



(1)

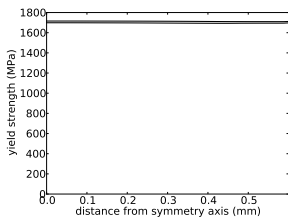
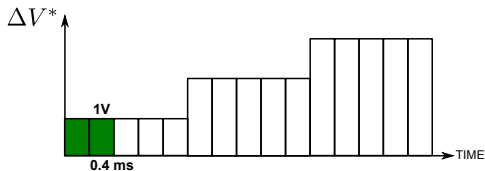
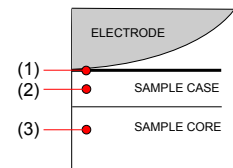


(2)

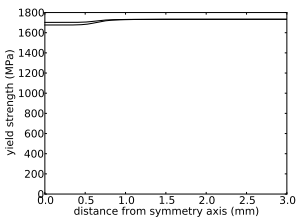


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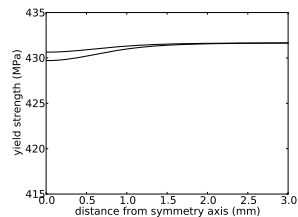
Results – Yield strength



(1)

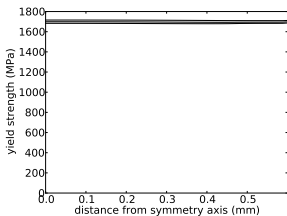
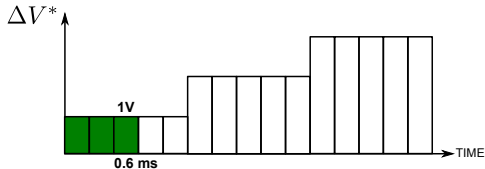
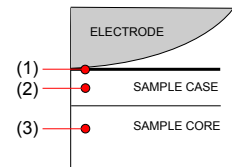


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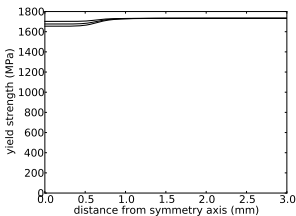


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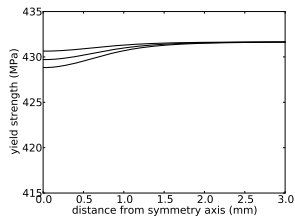
Results – Yield strength



(1)

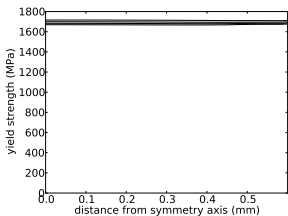
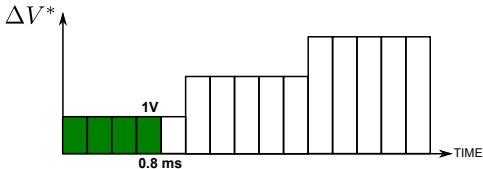
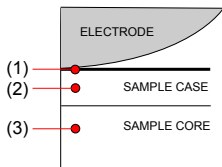


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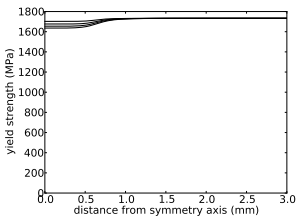


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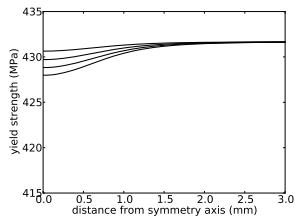
Results – Yield strength



(1)

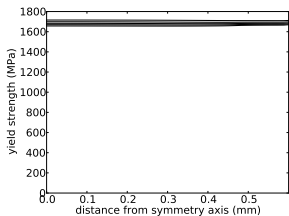
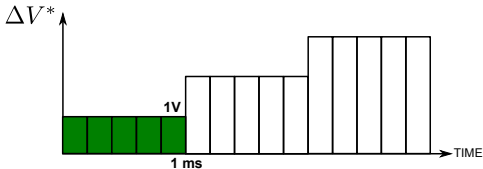
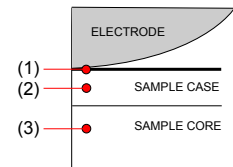


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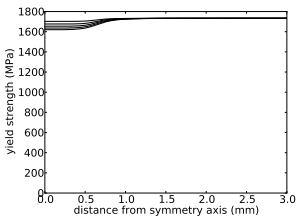


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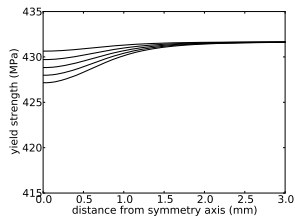
Results – Yield strength



(1)

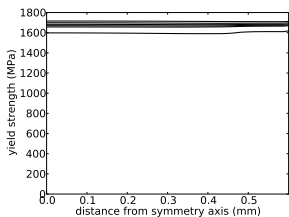
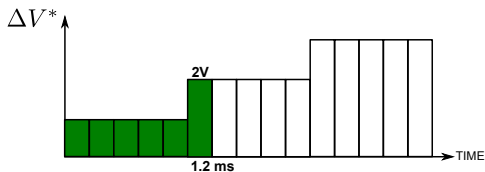
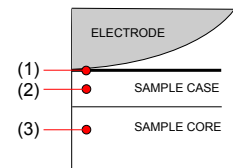


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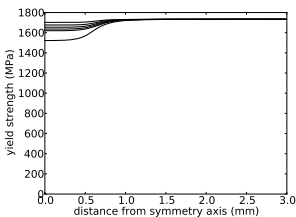


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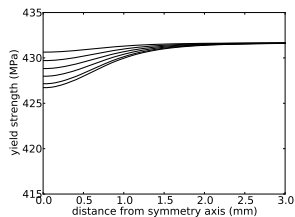
Results – Yield strength



(1)

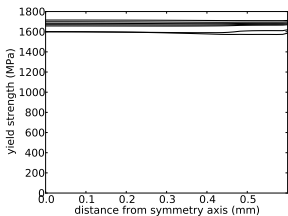
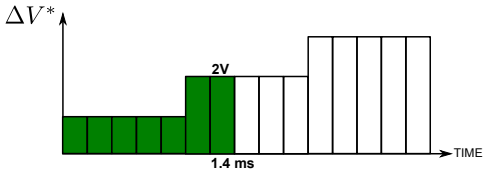
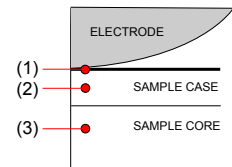


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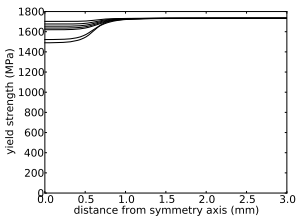


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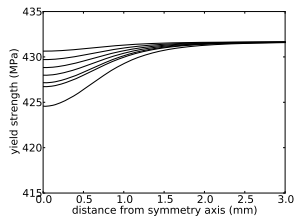
Results – Yield strength



(1)

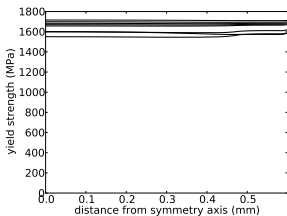
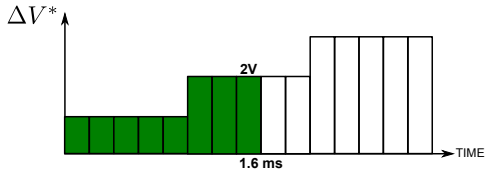
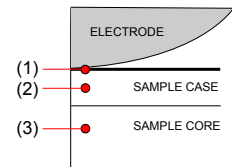


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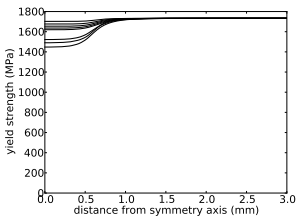


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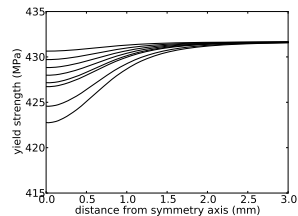
Results – Yield strength



(1)

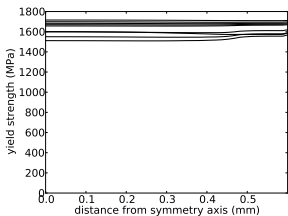
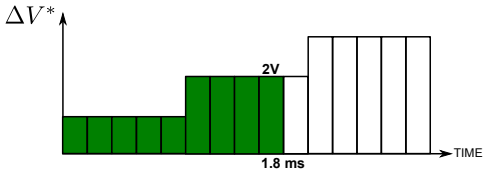
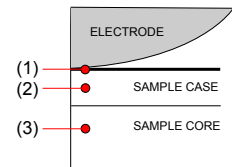


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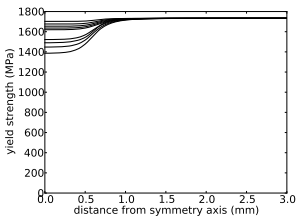


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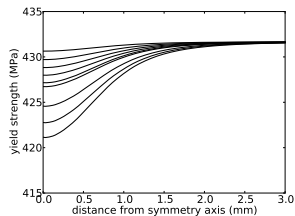
Results – Yield strength



(1)

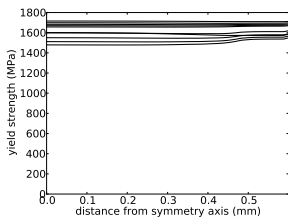
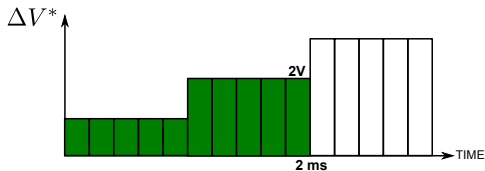
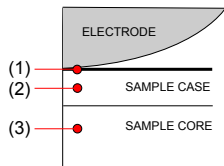


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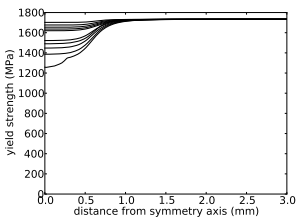


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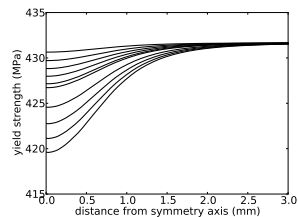
Results – Yield strength



(1)

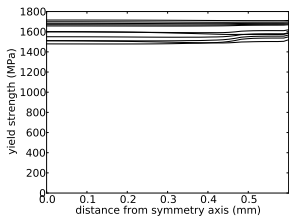
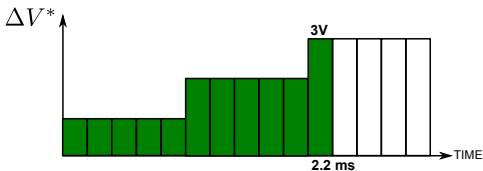
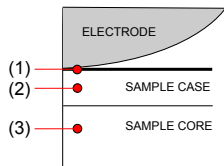


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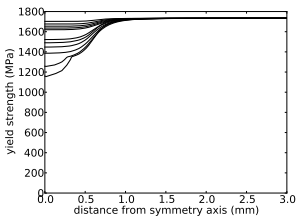


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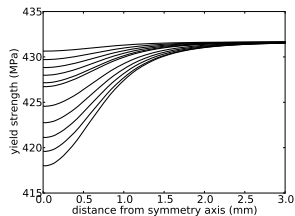
Results – Yield strength



(1)

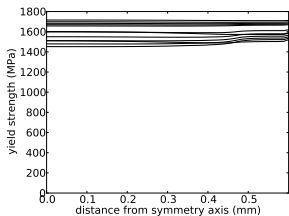
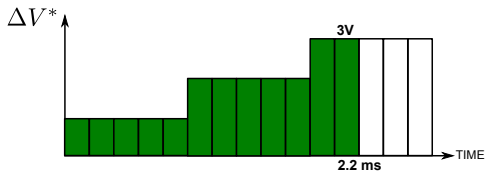
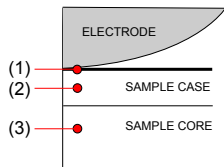


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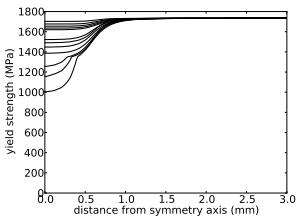


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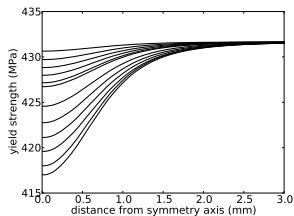
Results – Yield strength



(1)

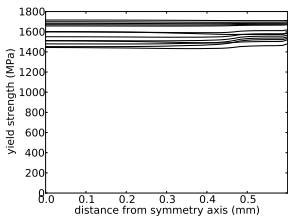
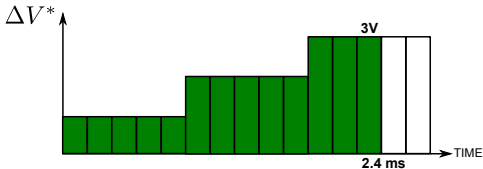
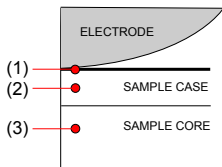


(2)

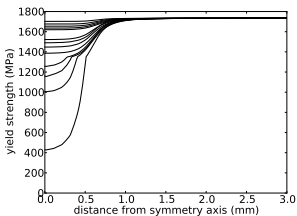


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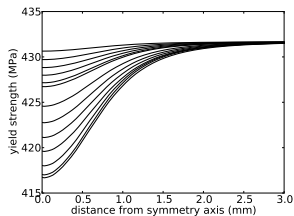
Results – Yield strength



(1)

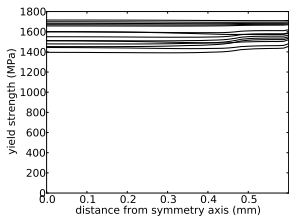
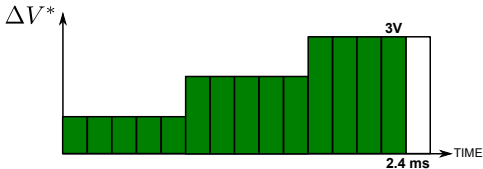
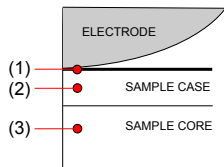


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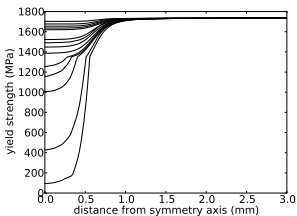


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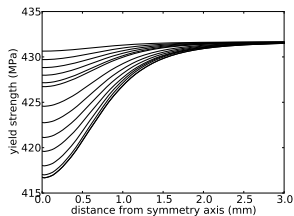
Results – Yield strength



(1)

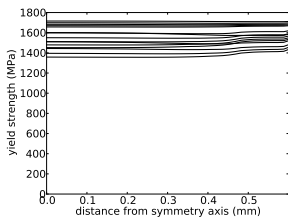
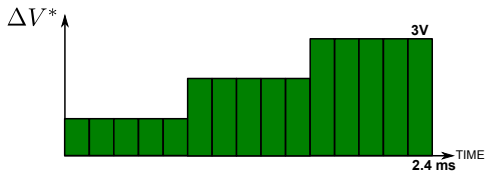
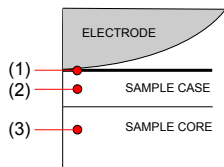


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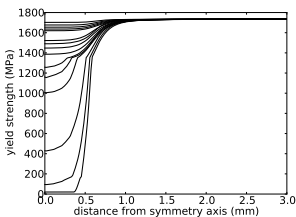


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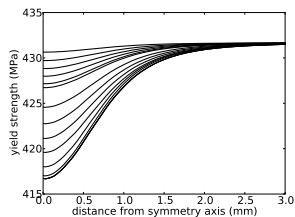
Results – Yield strength



(1)



(2)



(3)

Conclusions 1/2

- A coupling strategy suitable for general COMSOL architectures and solvers is designed to solve contact multiphysics involving steel samples
- The essential multiphysics of the real CDW process is taken into account by coupling mechanical, electrical, thermal and metallurgical fields
- A novel concept in the definition of non-linear properties of materials undergoing phase transformations is developed

Conclusions 2/2

- The overall model is able to capture a realistic behavior of steel sample during rapid CDW heating in terms of temperature and microstructure.
- The model allows to follow the behaviors of all the materials properties upon CDW, thus highlighting the peculiar aspects behind the physical problem
- Extension to spot welding, electrical circuitry and current-assisted powder metallurgy is possible
- Strong convergence difficulties are encountered when severe localized strain gradients develop