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

Paolo Di Napoli
Giovanni Maizza
Roberto Caglierio

Politecnico di Torino
Department of Materials Science and Chemical Engineering

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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
Heigth: 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

Master
Slave
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:
  \[ P_n = \frac{E_{\text{smxi}}}{h_{\text{min}} c_{\text{p1}} \text{smxi}} \cdot \min (1.0 \cdot 5^{\text{aug}}, 1) \]
- Initial contact pressure: 10 MPa
**Boundary conditions**

- Axial symmetry
- Applied pressure: 35 MPa
- Fixed edge of the sample
- Penalty factor:
  \[ P_n = \frac{E_{\text{maxi}}}{h_{\text{min}} c_{p1} \text{sm} \text{axi}} \cdot \min\left(1.e^{-3} \cdot 5^{\text{aug}}, 1\right) \]
- Initial contact pressure: 10 MPa
- Free displacement for the rest

---

**Model implementation – Structural**

Boundary conditions:

- Axial symmetry
- Applied pressure: 35 MPa
- Fixed edge of the sample
- Penalty factor: \[ P_n = \frac{E_{\text{maxi}}}{h_{\text{min}} c_{p1} \text{sm} \text{axi}} \cdot \min\left(1.e^{-3} \cdot 5^{\text{aug}}, 1\right) \]
- Initial contact pressure: 10 MPa
- Free displacement for the rest
STATIONARY ELECTRICAL
Model implementation – Electrical

Boundary conditions

- Axial symmetry
Model implementation – Electrical

Boundary conditions
- Axial symmetry
- Voltage drop $\Delta V^*$

Contact resistance
$\sigma_c = \rho_e^1 + \rho_e^2 / 4r_c$ [1]
Model implementation – Electrical

Boundary conditions

- Axial symmetry
- Voltage drop $\Delta V^*$
- Contact resistance

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

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

Model implementation – Electrical

Boundary conditions

- Axial symmetry
- Voltage drop $\Delta V^*$
- Contact resistance

\[ \sigma_c = \frac{\rho e_1 + \rho e_2}{4r_c} \quad [1] \]

\[ r_c = \text{contact radius} \]

- Electric insulation

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: $\dot{Q}_T = \frac{\sigma_c}{d} (V_1 - V_2)$

\[ \sigma_c = \frac{\rho e_1 + \rho e_2}{4r_c} \quad [1] \]

$r_c = \text{contact radius}$

Model implementation – Thermal

Boundary conditions

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

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

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

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

$T$ vs $\dot{T}$

$A_{c1}$ 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
- $\Psi_i$ 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
- $\Psi_i$ represents a general material property
- Properties values in pure $\alpha$ and pure $\gamma$ phase from experimental data
Model implementation – Phase transformation

- $A_{c1}$ and $A_{c3}$ curves from experimental data
- $\dot{T}$ defines univocally the phase fields
- $\Psi_i$ represents a general material property
- Properties values in pure $\alpha$ and pure $\gamma$ phase from experimental data
- Properties values in two-phase region obtained by sigmoidal function $f(lc1hs)$
## 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

\[ \Psi_S = \sigma_Y, E, E_{Tiso} \]

\[ \sigma, \varepsilon \]
Model implementation – Solution strategy

DC pulse discharge curve

\[ \Delta V \]

\( t \)

\[ \psi_S = \sigma_Y, E, E_{Tiso} \]

\[ \sigma, \varepsilon \]

pre-loading
Model implementation – Solution strategy

DC pulse discharge curve

pre-loading

\[ \Psi_S = \sigma_Y, E, E_{Tiso} \]

\[ \sigma, \varepsilon \]
Model implementation – Solution strategy

DC pulse discharge curve

pre-loading

\[ \Delta V_{n}^{*} \]

\[ \Delta t_{n}^{*} = t_{n+1}^{*} - t_{n}^{*} \]

\[ \Psi_{S} = \sigma_{Y}, E, E_{Tiso} \]

\[ \sigma, \varepsilon \]
Model implementation – Solution strategy

DC pulse discharge curve

\[ \Delta V_{n}^{*} \]

\[ \Delta t_{n}^{*} = t_{n+1}^{*} - t_{n}^{*} \]

Pre-loading

\[ dt_{\text{therm}} \]

CDW time step \( \Delta t_{n}^{*} \)

\[ T \]

\[ F \]

\[ a_{C} \]

\[ \Psi_{S} = \sigma_{Y}, E, E_{Tiso} \]

\[ \sigma, \varepsilon \]
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

DC pulse discharge curve

\[ \Delta V_n^* \]

\[ \Delta t_n^* = t_{n+1}^* - t_n^* \]

\[ \psi_S = \sigma_Y, E, E_{\text{Iso}} \]

\[ \psi_E = \rho_e \]

\[ \sigma, \varepsilon \]

\[ J, V \]
Model implementation – Solution strategy

DC pulse discharge curve

\[ \Delta V = \Delta V_n^* \]
\[ \Delta t_n^* = t_{n+1}^* - t_n^* \]

\( T \)

\( a_c \)

\( F \)

\( t_n^* \)

\( t_{n+1}^* \)

\( \Psi_S = \sigma_Y, E, E_{Tiso} \)

\( \Psi_E = \rho_e \)

\( \Psi_T = C_p, \alpha, k \)

\( \sigma, \varepsilon \)

\( J, V \)

\( T, \dot{T} \)
Model implementation – Solution strategy

DC pulse discharge curve

\[ \Delta t_n^* = t_{n+1}^* - t_n^* \]

Pre-loading

Structural: \( \Psi_S = \sigma_Y, E, E_{\text{Tiso}} \)
Electrical: \( \Psi_E = \rho_e \)
Thermal: \( \Psi_T = C_p, \alpha, k \)

\[ a_c, \Delta V_n^* \]

\[ T, \dot{T} \]
Model implementation – Solution strategy

DC pulse discharge curve

\[ \Delta V = 0 \rightarrow \Delta V_n^* \rightarrow 0 \]

\[ \Delta t_n^* = t_{n+1}^* - t_n^* \]

- Structural
  \[ \Psi_S = \sigma_Y, E, E_{Tiso} \]
  \[ \sigma, \varepsilon \]

- Electrical
  \[ \Psi_E = \rho_e \]
  \[ J, V \]

- Thermal
  \[ \Psi_T = C_p, \alpha, k \]
  \[ T, T \]

Pre-loading

\[ dt_{\text{therm}} \]

CDW time step \( \Delta t_n^* \)

\[ T \]

\[ A_{C1}, A_{C3} \]

\[ \gamma \]

\[ \alpha + \gamma \]

\[ A_{C1} \]

\[ \alpha \]

\[ T \]
Model implementation – Solution strategy

DC pulse discharge curve

\[ \Delta V^*_{n} \]

\[ \Delta t^*_n = t^*_{n+1} - t^*_n \]

\( T \)

pre-loading

Structural

Electrical

Thermal

\[ a_c \rightarrow \Psi_S = \sigma_Y, E, E_{Tiso} \]

\[ \Psi_E = \rho_e \]

\[ \Psi_T = C_p, \alpha, k \]

\[ \sigma, \varepsilon \]

\[ J, V \]

\[ T, T \]

\[ A_{c1}, A_{c3} \]

\[ A_{c3} \]

\[ \alpha + \gamma \]

\[ T \]
Model implementation – Solution strategy

DC pulse discharge curve

\[ \Delta V \]

\[ \Delta V_n^* \]

\[ \Delta t_n^* = t_{n+1}^* - t_n^* \]

\[ T \]

\[ d t_{\text{therm}} \]

CDW time step \[ \Delta t_n^* \]

pre-loading

\[ t_n^* \]

\[ t_{n+1}^* \]

**Structural**

\[ \Psi_S = \sigma, E, E_{Tiso} \]

\[ a_C \]

**Electrical**

\[ \Psi_E = \rho_e \]

\[ \dot{Q}_T \]

**Thermal**

\[ \Psi_T = C_p, \alpha, k \]

\[ A_{C1}, A_{C3} \]

**Phase transformation**

\[ \Psi_i \]

\[ \sigma, \varepsilon \]

\[ J, V \]

\[ T, T \]

phases
Model implementation – Solution strategy

DC pulse discharge curve

$t_n^*$  $dt_{therm}$  $t_{n+1}^*$

CDW time step $\Delta t_n^*$

$\Delta V_{n}^*$  $\Delta V_{n}$

$\Delta t_n^* = t_{n+1}^* - t_n^*$

$\Psi_S = \sigma_Y, E, E_{Tiso}$  $\Psi_E = \rho_e$  $\Psi_T = C_p, \alpha, k$  $\Psi_i = \sigma_Y, E, E_{Tiso}$

$\sigma, \varepsilon$  $J, V$  $T, \dot{T}$  phases  $\sigma, \varepsilon$
Model implementation – Solution strategy

DC pulse discharge curve

$t_{\text{end}}$

$\Delta V_{n}^*$

$\Delta t^*_n = t^*_{n+1} - t^*_n$

$T$

$\Delta V$

$dt_{\text{therm}}$

CDW time step $\Delta t^*_n$

pre-loading

$F$

$a_c$

$\Psi_S = \sigma_Y, E, E_{1,so}$

$\Psi_E = \rho_e$

$\Psi_T = C_p, \alpha, k$

$\Psi_i$

$\Psi_S = \sigma_Y, E, E_{\text{iso}}$

Structural

Electrical

Thermal

Phase transformation

Structural

$\sigma, \varepsilon$

$J, V$

$T, T$

phases

$\sigma, \varepsilon$
Results

- Structural
- Thermal
- Phase transformation
Results – Structural

Pre-loading

No Applied voltage
Elapsed time: 0 ms

ΔV

3V

2V

1V

0V

t

total plastic strain

Max: 0.0416

Min: −8.733e−4

distance from symmetry axis (mm)

0 0.5 1 1.5 2 2.5 3
CDW step:

Applied voltage $\Delta V^*$: 1 V
Elapsed time: 0.2 ms
Results – Thermal

CDW step:

Applied voltage $\Delta V^*$: 2 V
Elapsed time: 2.0 ms

Surface: Temperature (°C)
Arrow: total heat flux

Max: 679.286
Min: 24.85
Results – Thermal

CDW step:

Applied voltage $\Delta V^*$: 3 V  
Elapsed time: 3.0 ms

Graph showing the applied voltage over time with a step function, and a graph displaying temperature distribution with arrows indicating heat flux.
Results – Phase transformation

**CDW step:** focus on sample case

Applied voltage $\Delta V^*$: 3 V
Elapsed time: 2.2 ms

![Diagram of voltage over time and material phases]
Results – Phase transformation

**CDW step**: focus on sample case

Applied voltage $\Delta V^*$: 3 V

Elapsed time: 2.8 ms
CDW step: focus on sample case

Applied voltage $\Delta V^*$: 3 V
Elapsed time: 3.0 ms

![Diagram showing voltage change over time with phase transformation colors]
Results – Yield strength

\[ \Delta V^* \]

**ELECTRODE**

**SAMPLE CASE**

**SAMPLE CORE**

<table>
<thead>
<tr>
<th>TIME</th>
<th>0.2 ms</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>DISTANCE FROM SYMMETRY AXIS (mm)</th>
<th>0</th>
<th>200</th>
<th>400</th>
<th>600</th>
<th>800</th>
<th>1000</th>
<th>1200</th>
<th>1400</th>
<th>1600</th>
<th>1800</th>
</tr>
</thead>
<tbody>
<tr>
<td>YIELD STRENGTH (MPa)</td>
<td>0.0</td>
<td>0.5</td>
<td>1.0</td>
<td>1.5</td>
<td>2.0</td>
<td>2.5</td>
<td>3.0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(1) (2) (3)

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Results – Yield strength

\[ \Delta V^* \]

TIME

0.4 ms

0.0 0.1 0.2 0.3 0.4 0.5

distance from symmetry axis (mm)

0.0 0.5 1.0 1.5 2.0 2.5 3.0

yield strength (MPa)

415 420 425 430 435

distance from symmetry axis (mm)

415 420 425 430 435

yield strength (MPa)

(1)

(2)

(3)
Results – Yield strength

(1) (2) (3)

ELECTRODE

SAMPLE CASE

SAMPLE CORE

ΔV*

0.6 ms

TIME

yield strength (MPa)

0.0 0.5 1.0 1.5 2.0 2.5 3.0

distance from symmetry axis (mm)

0 200 400 600 800 1000 1200 1400 1600 1800

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Results – Yield strength

\[ \Delta V^* \]

- **ELECTRODE**
- **SAMPLE CASE**
- **SAMPLE CORE**

<table>
<thead>
<tr>
<th>TIME</th>
<th>0.8 ms</th>
<th>1V</th>
</tr>
</thead>
</table>

- **distance from symmetry axis (mm)**
  - 0
  - 200
  - 400
  - 600
  - 800
  - 1000
  - 1200
  - 1400
  - 1600
  - 1800

- **yield strength (MPa)**
  - 0.0
  - 0.5
  - 1.0
  - 1.5
  - 2.0
  - 2.5
  - 3.0

- **(1)**
- **(2)**
- **(3)**

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Results – Yield strength

ELECTRODE
SAMPLE CASE
SAMPLE CORE

\[ \Delta V^* \]

TIME
1 ms

0.0
0.1
0.2
0.3
0.4
0.5
distance from symmetry axis (mm)

yield strength (MPa)

0.0
0.5
1.0
1.5
2.0
2.5
3.0

0
200
400
600
800
1000
1200
1400
1600
1800

(1) (2) (3)

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Results – Yield strength

- ELECTRODE
- SAMPLE CASE
- SAMPLE CORE

ΔV* versus TIME

- 1.2 ms
- 2V

Graphs showing yield strength versus distance from symmetry axis for different sample cases:

(1) ELECTRODE
(2) SAMPLE CASE
(3) SAMPLE CORE

 yield strength (MPa)

 distance from symmetry axis (mm)
Results – Yield strength

ELECTRODE

SAMPLE CASE

SAMPLE CORE

TIME

1.4 ms

2V

\Delta V^*

(1)

(2)

(3)

yield strength (MPa)

distance from symmetry axis (mm)

0.0 0.5 1.0 1.5 2.0 2.5 3.0

0

200

400

600

800

1000

1200

1400

1600

1800

415

420

425

430

435

yield strength (MPa)

distance from symmetry axis (mm)

0

200

400

600

800

1000

1200

1400

1600

1800

0.0 0.1 0.2 0.3 0.4 0.5

distance from symmetry axis (mm)

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Results – Yield strength

- **ELECTRODE**
- **SAMPLE CASE**
- **SAMPLE CORE**

**ΔV**

1.6 ms

**TIME**

**yield strength (MPa)**

- (1)
- (2)
- (3)

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Results – Yield strength

- ELECTRODE
- SAMPLE CASE
- SAMPLE CORE

\[ \Delta V^* \]

Time: 1.8 ms

(1) (2) (3)

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Results – Yield strength

ELECTRODE
SAMPLE CASE
SAMPLE CORE

ΔV*

TIME

2 ms

yield strength (MPa)
distance from symmetry axis (mm)

(1) (2) (3)

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Results – Yield strength

ΔV*

3V

2.2 ms

(1) (2) (3)

ELECTRODE
SAMPLE CASE
SAMPLE CORE

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Results – Yield strength

![Graph showing yield strength vs distance from symmetry axis](image)

- **(1)**
- **(2)**
- **(3)**
Results – Yield strength

- ELECTRODE
- SAMPLE CASE
- SAMPLE CORE

ΔV* vs TIME

2.4 ms

3 V

Yield strength (MPa) vs distance from symmetry axis (mm)

(1) (2) (3)

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Results – Yield strength

(1) ELECTRODE
(2) SAMPLE CASE
(3) SAMPLE CORE

\[ \Delta V^* \]

TIME
2.4 ms

yield strength (MPa)

distance from symmetry axis (mm)

(1) (2) (3)

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Results – Yield strength

(Electrode) Sample Case
Sample Core

$\Delta V^*$

Time

2.4 ms

(1) (2) (3)

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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.
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.