Multidomain modelling of the magneto-mechanical behaviour of Dual Phase steels

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Outline

- Introduction
- Magneto-mechanical behaviour of DP steels
- Origin of the magneto-mechanical behaviour
- Multidomain modelling
- Multidomain modelling of DP steels
- Conclusions
Introduction

Heat Treatment of DP steels

microstructure fluctuation

$$\Delta T \rightarrow \Delta \% \text{phases}$$

consequences

- Mechanical behaviour

Phase diagram of a steel

T(°C)

%C

850
700

γ + α

α + α'

γ

α

γ austenite

primary nucleates composition $c_n$, $c_n$

α grows composition $c_n$, $c_n$

$A_3$

$\gamma + \alpha$

$\gamma$

Cold Rolling

Hot Rolling

Quenching

850 °C

700 °C
The mechanical behaviour of a DP steel exhibits both high strength and high ductility. These properties come from the dual phases microstructure (ferrite $\alpha$ + martensite $\alpha'$).
Introduction

Industrial context

- **Microstructure identification by magnetic NDT measurement**
  - influence of the process (hot rolling, quenching,...) on the microstructure.
  - mechanical behaviour due to the microstructure

- **No prediction nowadays**
  - unknown phases behaviour.
  - empirical identification

**research context**

- **coupled modelling of the magneto-mechanical behaviour**
  - phase modelling (*ferrite / martensite*)
  - heterogeneous microstructure (*localization*)
  - inverse identification

- **main problems**
  - magneto-elastic coupling
  - phases behaviour
  - computing time
Magneto-mechanical behaviour of DP steels

Magnetization $\vec{M}(H)$
Magnetostriiction $\varepsilon^H(\vec{M})$
strain
heterogeneous media

%martensite
composition
$= \mathcal{F}(T)$

dual phase microstructure

ferromagnetic media
Magneto-mechanical behaviour of DP steels

- Specimen
- Strain Gauges
- Secondary Coïlling \((B-Coil)\)
- Primary Coïlling \((P-Coil)\)
Magneto-mechanical behaviour of DP steels

influence $\Delta T$ on DP steel behaviour

<table>
<thead>
<tr>
<th></th>
<th>DP #1</th>
<th>DP #2</th>
<th>DP #3</th>
<th>DP #4</th>
<th>DP #5</th>
<th>DP #6</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_y$ (MPa)</td>
<td>473</td>
<td>480</td>
<td>467</td>
<td>467</td>
<td>479</td>
<td>472</td>
</tr>
<tr>
<td>$\sigma_{max}$ (MPa)</td>
<td>787</td>
<td>793</td>
<td>785</td>
<td>785</td>
<td>791</td>
<td>785</td>
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</tbody>
</table>

mechanical properties

Magnetic behaviour

Magnetostrictive behaviour
Multidomain modelling

Single crystalline Modelling

Hypothesis
- Domains homogeneous magnetization
- Grains homogeneous stress & strain
- Cubic symmetry
- Loading direction $\vec{H} = h.\vec{n}_c$

Magnetic microstructure: Fe 3%Si

[Habert, 1998]

simplified vision of the magnetic microstructure
(cubic anisotropy)

Magnetic free energy [Daniel 2008]

$$\mathcal{W}^\alpha = \mathcal{W}_z^\alpha + \mathcal{W}_a^\alpha + \mathcal{W}_\sigma^\alpha$$

$$\mathcal{W}^\alpha = -\mu_0 \vec{H}.\vec{M}^\alpha + K_1 \left( \gamma_1^2 \gamma_2^2 + \gamma_2^2 \gamma_3^2 + \gamma_1^2 \gamma_3^2 \right) - \sigma : \epsilon^\alpha_{\mu}$$
Multidomain modelling

Single crystalline modelling

State variables
- Magnetization direction of each domain \((\phi_{\alpha}, \theta_{\alpha})\)
- Volume fraction of a domain \(f_{\alpha}\)

\[\theta_{\alpha} \in [0, \pi] \quad \phi_{\alpha} \in [0, 2\pi]\]

Analytic minimization
\[ (\phi_{\alpha}, \theta_{\alpha}) = \min(W_{\alpha}) \]

Constitutive laws
\[ \phi_{\alpha}(H, \sigma, \bar{n}_c) \quad \theta_{\alpha}(H, \sigma, \bar{n}_c) \]

Stochastic constitutive law
\[ f_{\alpha} = \frac{\exp(-A_sW_{\alpha})}{\sum_{\alpha} \exp(-A_sW_{\alpha})} \quad \sum_{\alpha} f_{\alpha} = 1 \]

Homogenization
\[ \bar{M} = \sum_{\alpha} f_{\alpha}\bar{M}_{\alpha} \quad \epsilon^\mu = \sum_{\alpha} f_{\alpha}\epsilon_{\alpha}^\mu \]
The polycrystalline magnetic and magnetostrictive behaviour is similar to the single crystal behaviour loaded along a specific direction « mean direction » of the crystal.
Multidomain modelling

Polycrystalline modelling

Polycrystal hypothesis
- ISOTROPIC
- HOMOGENEOUS FIELD

An isotropic polycrystal loaded along one direction corresponds to a single crystal loaded along all directions.

Single crystal hypothesis
- CUBIC SYMMETRY

For cubic structure, a loading direction finds its equivalence inside the standard triangle.

what is the equivalent loading direction (of the single crystal) we could use to compute the polycrystalline behaviour with a single crystalline modelling?
**Multidomain modelling**

Polycrystalline modelling

Search for the optimal loading direction of the single crystal

The first approximation is to consider the single crystal behaviour as **ISOTROPIC** and search for an average direction of the standard triangle

The first approximation is to consider the single crystal behaviour as **ISOTROPIC** and search for an average direction of the standard triangle.

**ISOTROPIC**

\[ \vec{n} = \langle \vec{n}_i \rangle \]

**HOMOTHETIC ANISOTROPY**

\[ \vec{n} = \beta \vec{n}_i \]

**ANISOTROPY**

\[ \vec{n} = F(\beta, \vec{n}_i, \vec{H}, \sigma) \]
Multidomain modelling

**Polycrystalline modelling**

Average direction

\[
\bar{n} = \frac{1}{S} \iint \bar{n}_i \, dS
\]

\[
\bar{n} = \left( \frac{\cos \phi \sin \theta}{\sin \phi \sin \theta}, \cos \theta \right)
\]

\[
(\phi, \theta) = (38^\circ, 77^\circ)
\]

Optimization of angles is required to take account single crystal anisotropy
Multidomain modelling

Dual Phase modelling: Localization

- modelling choices $\implies$ Magnetic inclusions surrounded by the equivalent homogeneous media

\[
\bar{H}_i = \bar{H} + \frac{1}{3 + 2\chi_o} (\bar{M} - \bar{M}_i) \bar{H}_{di}
\]

\[
\sigma_i = \Sigma + C : (I - S^E) : (\varepsilon_i^\mu - \varepsilon^\mu_i) \sigma_i
\]

\[S^E = Eshelby's\ tensor\]

\[
\bar{M} = f_{fe} \bar{M}_{fe} + f_m \bar{M}_m
\]

\[
\varepsilon^\mu = f_{fe} \varepsilon^\mu_{fe} + f_m \varepsilon^\mu_m
\]

\(f_m = martensite\ fraction\)

\(f_{fe} = ferrite\ fraction\)
Multidomain modelling

- ferrite / martensite modelling results

- ferrite (well known)

- martensite (unknown magnetic properties)

A C38 carbon steel has been considered (wt%C=0.38%).

C38 as cast

100% martensitic microstructure, close to DP steels
martensitic phase

C38 quenched
Multidomain modelling

- ferrite / martensite Modelling results

- model parameters and physical constants

<table>
<thead>
<tr>
<th></th>
<th>ferrite</th>
<th>martensite</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_c(\degree)$; $\phi_c(\degree)$</td>
<td>88; 41</td>
<td>90; 36</td>
</tr>
<tr>
<td>$\lambda_{100}$</td>
<td>$21 \times 10^{-6}$</td>
<td>$-21 \times 10^{-6}$</td>
</tr>
<tr>
<td>$\lambda_{111}$</td>
<td>$3.1 \times 10^{-6}$</td>
<td>$10 \times 10^1$</td>
</tr>
<tr>
<td>$K_1(J.m^{-3})$</td>
<td>4, $8 \times 10^3$</td>
<td>$1.71 \times 10^6$</td>
</tr>
<tr>
<td>$M_s(A.m^{-1})$</td>
<td>$1.05 \times 10^6$</td>
<td>$3.5 \times 10^{-3}$</td>
</tr>
<tr>
<td>$A_s(m^3.J^{-1})$</td>
<td>$4 \times 10^{-4}$</td>
<td></td>
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</tbody>
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Multidomain modelling of aDP steel

Dual Phase Modelling results

Magnetic and magnetostrictive behaviour for different volume fractions of martensite

![Graphs showing magnetic and magnetostrictive behaviour](image-url)
Multidomain modelling of aDP steel

Dual Phase modelling : Localization

Application: inverse identification

Local fields convergence

\[ \bar{H}_{\text{mean}} = 1.25 \times 10^3 \, A.m^{-1} \]

Localization influence on the behaviour

\[ f_m \approx 36\% \]
Multidomain modelling of aDP steel

Dual Phase modelling: Homogenization

Inversion identification: 36% martensitic media

Experimental VS Modelling results

\[ f_m \approx 36\% \]
Conclusion

Positive aspects

- Fast estimation of the magneto-mechanical behaviour of a dual phase microstructure.
- Fast convergence.
- Accessible modelling.

Negative aspects

- Overestimation of the magnetostrictive behaviour, due to homogeneous stress hypothesis
- Simplified modelling: low contrast between two isotropic polycrystals.
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