Multiscale modelling of thermo-mechanical deformation for the design, processing and behaviour of structural alloys

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Background and motivation

Introduction

- Metallic alloys are needed for nearly all sectors of commercial enterprise/industrial activity.
- Examples include energy production/conversion, transportation—e.g. aerospace, automotive and shipping, construction and manufacturing, space and satellite communications. . . ..
- Primary metal production, alloy creation and design, integrated metallic products and alloy recycling account for 46% of all EU manufacturing value and ~11% of EU gross domestic product [1].
- But modelling and simulation methods are needed for the rapid invention and prototyping of new metallic products.
- Multiscale modelling across a range of length scales is a prerequisite for this.

Research activities: overview

Introduction

Superplastic forming

Student: Enrique Alabort
Superplasticity: a three-scale study

Deformation mechanisms

Length scale

Materials science
Engineering

Continuum modelling
Industrial application

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The deformation mechanisms

800°C

700°C

900°C
The continuum characterisation

Superplasticity

Microstructurally-based material model

High-temperature mechanical characterisation

The industrial application

Superplasticity

Twist and camber

Hot creep forming

Superplastic forming
Flexible forming

Researcher: Jianglin Huang

Flexible forming: overview & partners

- Flexible forming process design for closed-loop control
- Rapid process modelling for closed-loop control
- Close loop control of material properties in flexible forming processes.
- Application case studies
Flexible forming: case studies

Transformative manufacturing processes

Researcher: Fauzan Adziman
Novelty: Integration of microstructurally-sensitive models to the manufacturing processes.

**Research framework**

**Transformative processes**

**Modelling**

- Physically-based mechanics: (a) slip systems, (b) phase transformation, (c) dislocations.
- Effective representation of: (a) interface, (b) phase transformation.
- Analysis by means of: (a) crystal plasticity, (b) FEM.

**Manufacturing parameters and optimization studies**

**Simulation results**

- High temperature, high speed, etc.
- Target: achieve target state. (e.g., velocity) from an accurate model. (e.g., FEM).

**Industrial partnerships**

**Modelling material behaviour**

**Transformative processes**

2A-i. Physics-based composition-dependent crystal plasticity

Coupled with

<table>
<thead>
<tr>
<th>Strain</th>
<th>Yield stress</th>
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<tbody>
<tr>
<td>{$\sigma_{y}$}</td>
<td>{$F$}</td>
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The resolved shear stress

{$\tau = \dot{\gamma} \tau$}

Evolution equations for the plastic deformation gradient

{$F = \sum_{i,j} F_{ij} \, \dot{\gamma}_{ij}$}

Evolution equations for the mobile dislocation density

{$\rho = \rho_{0} \left( 1 - \frac{\rho_{0}}{\rho_{s}} \right) \ln \left( \frac{\rho}{\rho_{0}} \right)$}

Dislocations-based slip rate:

{$\dot{\gamma}_{ij} = \frac{1}{A_{ij}} \frac{\partial \phi}{\partial x_{j}}$}

Simulation results
Modelling continuum behaviour

Transformative processes

Process zone – integrated multi-scale modelling

A schematic example of the integrated multi-scale modelling

Thermomechanical coupling transformations

\[ \mathbf{Q}_i = \mathbf{Q}_i(\mathbf{u}_i, \mathbf{p}_i); \quad i = 1, \ldots, n_{\text{tot}} \]

Transformative flow (flow rule)

\[ \mathbf{F} = \nabla \mathbf{u} + \mathbf{D} \mathbf{K} \mathbf{D}^T \]

where \( \mathbf{F} \) is the work conjugate of transformation deformation gradient.

Process modelling

Transformative processes

Rotary friction welding

A 2.5D axisymmetric model

High-speed machining

3D model
Conclusions

• A wide range of metal forming processes are being modelled at different strain rates and temperatures.

• The mechanical characterisation of materials is crucial. A new mechanical testing lab is being constructed in Oxford.

• Multi-scale and physically based models are the trend in metal forming processes.

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