MINI – CAS ON MECHANICAL ENGINEERING

METAL FORMING (INSIGHTS ON)

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A «process» conceived to produce, starting from a semifinished product, parts with the desired shape and the desired properties (e.g. mechanical properties, corrosion behaviour, roughness and so on).

Material forming: the «science» that studies these processes
Introduction

INFLUENCE OF THE BASE MATERIAL ON THE PROCESS EFFECTIVENESS
**Introduction**

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>v = 0.01 s⁻¹</th>
<th>v = 0.1 s⁻¹</th>
<th>v = 1 s⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>900°C</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
<tr>
<td>1000°C</td>
<td><img src="image4.png" alt="Image" /></td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
<tr>
<td>1100°C</td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
<td><img src="image9.png" alt="Image" /></td>
</tr>
</tbody>
</table>

**INFLUENCE OF THE PROCESS ON FINAL MICROSTRUCTURE OF THE PART**
**Experimental: Forging Tests**

Test at $T=940-960^\circ C$: filling defect (corner)

Test at $T=1100^\circ C$, better material flow (flash);

«Buy to Fly» Ratio: $R_f = 4$
Introduction

FORGED IN ALPHA FIELD

FORGED IN BETA FIELD
Introduction

1. How the material behaves?
2. Material cannot be seen as a black box
3. Which is the structure of the material?
4. Which are the mechanisms ruling the forming process?

HOW TO APPLY AND «CALIBRATE» THE ABOVE ACTIONS TO OBTAIN THE DESIRED PART WITH THE DESIRED PROPERTIES
Common metallic crystal structures

- body-centred cubic (bcc)
- face-centred cubic (fcc)
- hexagonal close-packed (hcp)

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Cold Plastic Deformation Basic

(A) Edge dislocation  (B) Gilde (conservative)  (C) Climb (non-conservative)

(D) Screw dislocation  (E) Gilde (conservative)  (F) Cross slip (conservative)

Interstitial dislocation loops gather inside helical dislocations
Helical dislocations grow by vacancy absorption

Scale: 1 μm  50 nm
Plastic Deformation

- Slip forms small steps of crystal resulting from large dislocations along same plane
- Schmidt law – stress reqd to initiate slip in a Pure single crystal is constant at a given temp
  - All planes don’t have same RSS for given load. Deformation to start on plane having max RSS
Cold Plastic Deformation Basic

Stages of Plastic Deformation

Adapted from Fig. 7.1, Callister 7e.
Cold Plastic Deformation Basic

Slip

Slip Plane (111)

Slip Direction

Twinning

Twinning Plane (111)

Twinning Direction
Cold Plastic Deformation Basic

Slip v/s Twinning

<table>
<thead>
<tr>
<th>Slip</th>
<th>Twinning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomic movement</td>
<td>fractional atomic spacing</td>
</tr>
<tr>
<td>whole number of atomic spacing</td>
<td></td>
</tr>
<tr>
<td>Microscopic appearance</td>
<td>Wide bands or broad lines</td>
</tr>
<tr>
<td>Thin lines</td>
<td></td>
</tr>
<tr>
<td>Lattice orientation</td>
<td>Lattice orientation changes</td>
</tr>
<tr>
<td>No change in lattice orientation</td>
<td></td>
</tr>
<tr>
<td>Time</td>
<td></td>
</tr>
<tr>
<td>many milli sec</td>
<td>few micro sec</td>
</tr>
<tr>
<td>RSS</td>
<td>no role</td>
</tr>
</tbody>
</table>

Undeformed Crystal  
After Slip  
After Twinning
Cold Plastic Deformation

(a) $\varepsilon_{eq} = 0.00$
(b) $\varepsilon_{eq} = 0.050$
(c) $\varepsilon_{eq} = 0.056$
(d) $\varepsilon_{eq} = 0.058$
(e) $\varepsilon_{eq} = 0.061$
(f) $\varepsilon_{eq} = 0.1$
Cold Plastic Deformation Basic

(A) Closed packed planes, atoms can slip easily

(B) Not so closed packed planes, atoms slip not so easily

Plastic Flow – Planes of atoms slip past one another
Cold Plastic Deformation Basic

FCC SLIP SYSTEM

- The slip plane belongs to the (111) family
- Slips occur at <110>-type direction, within (111) planes
- There are several slips direction for a slip plane, forming different possible combination of slip system
- For FCC, 4 unique (111) planes and 3 independent <110> directions, results in 12 slips system.
# Major Slip Systems

<table>
<thead>
<tr>
<th>Crystal structure</th>
<th>Slip plane</th>
<th>Slip direction</th>
<th>Number of slip systems</th>
<th>Unit-cell geometry</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>bcc</td>
<td>(110)</td>
<td>(111)</td>
<td>$6 \times 2 = 12$</td>
<td>[Diagram]</td>
<td>$\alpha$-Fe, Mo, W</td>
</tr>
<tr>
<td>fcc</td>
<td>(111)</td>
<td>(110)</td>
<td>$4 \times 3 = 12$</td>
<td>[Diagram]</td>
<td>Al, Cu, $\gamma$-Fe, Ni</td>
</tr>
<tr>
<td>hcp</td>
<td>(0001)</td>
<td>(11\overline{2}0)</td>
<td>$1 \times 3 = 3$</td>
<td>[Diagram]</td>
<td>Cd, Mg, $\alpha$-Ti, Zn</td>
</tr>
</tbody>
</table>
Cold Plastic Deformation

- Initial coarse grain
- Dislocation wall
- Dislocation cell

(a) Initial coarse grain
(b) Dislocation wall
(c) Dislocation cell

(d) Subgrain with low angle grain boundary
(e) Refined grain with high angle grain boundary
(f) Nanocrystalline grain
Cold Plastic Deformation Basic
Cold Plastic Deformation Basic

- Cold-rolled
- 550 °C anneal for 1 hour
- 650 °C anneal for 1 hour

Rolling direction
Material Properties

[Graph showing stress-strain relationship with labels:
- A: Stress
- B: Yield Strength
- C: Ultimate Strength
- D: Fracture
- Strain Hardening
- Necking
- % Elongation]

Image of a tensile test specimen.
Material Properties

Forming Limit Diagram
Material Properties

Relaxation test

\[ \sigma = \sigma(t) \]

\[ \sigma_0 \]

\[ \varepsilon_{pl} \]

\[ t_0 \]

friction stress

\[ T \]
Material Properties

Compression test

[Graphs showing compression test results with different temperatures and strain rates.]
Material Properties

**Jhonson Cook Model – a constitutive equation for metals**

\[ \sigma = (A + B\varepsilon^n)(1 + C\ln\dot{\varepsilon}^*)\left(1 - T^*m\right) \]

- Work hardening
- Strain rate
- Thermal softening
By the *primary stress* in the deformation zone.

Further classification by kinematics, tool geometry and workpiece geometry leading to more than 200 basic processes!
Forming Processes

Metal Forming Processes

A KEY MADE OF DIFFERENT PIECES, MADE OF DIFFERENT DISCIPLINES
Radio Frequency Dipole Cavity: why F.E.?

Shaping + Electron beam welding of the sub-components

Manufacturing Challenges:
1. Large deformation processes (deep drawing, hole extrusion..)
2. Multiple shaping processes on 4mm thick Niobium sheets
3. Tight geometrical tolerances (±0.1mm)

FEM analyses
- Better understanding of the physical phenomena involved in the process
  - Determining process feasibility
- Faster iteration on the design of the fabrication tools
CERN Applications

Bowl Case Study: Deep drawing

- High straining of material
- High compressions
- Wrinkles and Puckering

FEM analyses to
- Speed up tool design
- Steer manufacturing choices
Multicell RF cavity

- Convection Gauge
- Gas-Out Port (Pumping Port)
- Fundamental Power Coupler (FPC)
- Field Probe (FP)
- Convectron Gauge
- Cold RF Window
- Warm RF Window
- 5 Cell SRF Cavity (1.5 GHz)
- View Port
- Gas-In Port
- FWD/REF Power Meter
- Trans Power Meter
CERN Applications

Hydroforming of tubes

1. Insertion of tube and closing of tooling
2.
3. Hydroforming by pressurisation and axial feeding
4. Opening of tooling for removal of part
Figure 2.6: The three typical stress regions during tube hydroforming.
CERN Applications

Hydroforming of tubes
Interesting processes: single point incremental forming
Interesting processes: single point incremental forming

- (a) Sheet metal part, Forming tool, Full die
- (b) Sheet metal part, Partial die
- (c) Sheet metal part, Forming tool, Static fixture
- (d) Sheet metal part, Forming tool, Kinematic support
Interesting processes: single point incremental forming
CONCLUDING REMARKS

- KNOW THE MATERIAL YOU ARE USING
- KNOW THE MECHANISMS RULING FORMING
- CHARACTERIZE THE PROPERTIES OF THE SPECIFIC RAW MATERIAL YOU ARE USING
- KNOW THE PROPERTIES YOU WANT IN THE FINAL PART
- FIND OUT A CONSTITUTIVE LAW
- CAREFULLY CHOSE THE FORMING PROCESS
- MORE THAN CAREFULLY CALIBRATE YOUR PROCESS
- (OFF) TOPIC: KNOW TOOLS AND FACILITIES USED AND REQUIRED
Thanks!!!
Any question?

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SUGGESTED READINGS

Cahn, Physical Metallurgy
Cottrell, Dislocations and Plastic Flow in Crystals
Dieter, Mechanical Metallurgy