Role of microstructure in modeling of manufacturing Processes

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Engages in research, education, training, technology development and related activities in most areas of technology, science & management

- 530 acres (5.3 sq. km) of campus area
- 15 Departments, 1 School, 4 IDPs & 9 Centers
- ~600 fulltime faculty & 90 adjunct faculty
- ~1300 support staff
- ~9600 students (P.G ~ 6000; PhD~2000)
- ~750 project research staff

| Patents (India and Foreign) 2012-2013 | >100 |
| Number of industries which come to us for projects | >2000 |
| Research funding in INR (Governmental & Industrial, 2012-13) | ~300 Cr |
| Number of technology spinoffs from IITB technologies | >50 |
Overview of NCAIR

**Vision**
- Create a World Class Aerospace Ecosystem in India

**Mission**
- To be a catalyst for collaboration between industry, Academia, R&D Organizations and Government
- To provide economically viable and sustainable solutions
- To promote Innovation, Knowledge Creation and Entrepreneurship
- To disseminate knowhow and develop human resources

**Inception** 19th November 2010

**Key Strategic Technologies**
- Machining
- Forming
- Casting

**Scope of Materials**
- Titanium
- Super Alloys
- Composites
- Aluminum, Magnesium, AHSS

**Stake-holders**
- DST
- IIT-B
- BOEING
- NAL
- HAL
- Sandvik
- Delcam
- DMG-Mori Seiki

**Services of NCAIR**
- **Core Services**
  - R&D Projects
  - Technology Transfer
- **Enabling Services**
  - Specialized Training Programs
  - Adv Aero Mfg and testing facilities for R&T Activities
  - Mentoring and business Services

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<table>
<thead>
<tr>
<th>Faculty members</th>
<th>Previous affiliations</th>
<th>Faculty members</th>
<th>Previous affiliations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prof. Suhas Joshi</td>
<td>IIT-Bombay, UIUC</td>
<td>Prof. B. Ravi</td>
<td>IISc Bangalore, Purdue U</td>
</tr>
<tr>
<td>Prof. Asim Tewari</td>
<td>Georgia Tech, GM Global R&amp;D</td>
<td>Prof. Ramesh Singh</td>
<td>Georgia Tech</td>
</tr>
<tr>
<td>Prof. S.S.Pande</td>
<td>IIT-Bombay, U. Of Cincinnati</td>
<td>Prof. Sushil Mishra</td>
<td>IIT-Bombay, GM Global R&amp;D</td>
</tr>
<tr>
<td>Prof. Prita Pant</td>
<td>Cornell University</td>
<td>Prof. V. Kartik</td>
<td>Carnegie Mellon U, IBM Research</td>
</tr>
<tr>
<td>Prof. Shiva G.</td>
<td>University of Massachusetts Amherst</td>
<td>Prof. Parag Tandaiya</td>
<td>IISc Bangalore, Caltech, USA</td>
</tr>
<tr>
<td>Prof. Rajneesh Bharadwaj</td>
<td>Johns Hopkins University, Baltimore</td>
<td>Prof. Rakesh G Mote</td>
<td>Nanyang Technological University, Singapore</td>
</tr>
</tbody>
</table>

CORE FACULTY - IITB (NCAIR)
What is microstructure?

A microstructure is an arrangement of volumes, internal surfaces, lines, and points.

Volumes: Voids, fibers, inclusions, particles, grains, etc.
Surfaces: Micro-crack surfaces, grain boundaries, inclusion interfaces, etc
Lines: Dislocation lines, micro-crack tips, grain edges, triple lines, etc.
Points: Quadruple points, particle/grain centers, atoms, etc.

Texture is a part of structure and thus microstructure

**Most general definition**

Microstructure is a spatially (and/or temporally) varying $d$ dimensional data structure.
Modalities of acquisition

- Optical
- SEM
- TEM
- AFM
- SPM
- X-ray CT
- PET, MRI, SIMS, etc.
Quantum size Effects

Surface/Interface Effects

Human Hair

Nano Tubes (diameter)

Microscale

Nanoscale

Atoms

Molecules

Second Phase Particles

Nano Tubes (length)

Clusters

Nano Particles

Self-assembly

Ultrafine Particles

Current MEMS

Nano Tubes (diameter)

Dislocations

Precipitates

DNA (width)

Surface Structures

DNA (length)

Self-assembly

Precipitates

Clusters

Surface Structures

DNA (length)

DNA (width)

Surface/Interface Effects

Quantum Dots

Nano Particles

Ultrafine Particles

Quantum Dots

Transistors

Human Hair

Gas pores

Grains

Dendrite arm spacing

Larger to smaller

0.1 nm

1 nm

10 nm

100 nm

1000 nm

10000 nm

100000 nm
Problem of spheres in 3D

For a collection of spheres of different sizes in 3D which of the following is true:

1.) Mean circle size in 2D is less than mean 3D sphere size
2.) Mean circle size in 2D is greater than mean 3D sphere size
3.) Mean circle size in 2D is equal to mean 3D sphere size
Non-trivial problem

On a unit line segment choose two random points $x_1$ and $x_2$. If the points are $d$ distance apart (without regard to ordering), what value of $d$ has the highest probability?

$$P(d) = \frac{\int_{0}^{1} \int_{0}^{1} \delta(d - |x_2 - x_1|) \, dx_1 \, dx_2}{\int_{0}^{1} \int_{0}^{1} dx_1 \, dx_2} = 2 (1 - d),$$
Stereology : True three-dimensional probe

- Pioneering work on
  - 3D spatial statistics
  - topological connectivity
  - Euler-Poincare

- Approach
  - through 3D reconstruction
  - grains modeled as ext. convex rings

- Materials System
  - A356 alloy
  - AA5754 alloy
  - AZ31 alloy
  - THA
Case Study 1
Titanium alloy machining
Motivation

Gas turbine engine, compressor parts, airframe structure, Landing gear disc
Percentage of Airframe Titanium vs. Year of Rollout—Commercial Transports
Titanium Value Chain—Forgings

Cumulative Normalized Cost

- Percentage Cost
- Cumulative Cost

% Cost by Stage

Sponge
Raw Alloying Addns
Billet Conversion
Forging (roughed)
Machining
Shipping
Effect of c/a Ratio on slip systems of HCP crystals

Typical slip systems observed in some HCP metals

<table>
<thead>
<tr>
<th>Element</th>
<th>c/a</th>
<th>Deviation (%) from the ideal c/a = 1.633</th>
<th>Principal slip system</th>
<th>Secondary slip system</th>
<th>Other slip system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cd</td>
<td>1.886</td>
<td>+15.5</td>
<td>Basal {0001}{11\bar{2}0}</td>
<td>Pyramidal {1\bar{1}\bar{2}}{1\bar{1}\bar{2}}</td>
<td>Prismatic {10\bar{1}0}{11\bar{2}0}</td>
</tr>
<tr>
<td>Zn</td>
<td>1.856</td>
<td>+13.6</td>
<td>Basal {0001}{11\bar{2}0}</td>
<td>Pyramidal {1\bar{1}\bar{2}}{1\bar{1}\bar{2}}</td>
<td>Prismatic {10\bar{1}0}{11\bar{2}0}</td>
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<tr>
<td>Mg</td>
<td>1.624</td>
<td>−0.6</td>
<td>Basal {0001}{11\bar{2}0}</td>
<td>Prismatic {10\bar{1}0}{11\bar{2}0}</td>
<td>Pyramidal {10\bar{1}1}{11\bar{2}0}{11\bar{2}2}{11\bar{2}3}</td>
</tr>
<tr>
<td>Co</td>
<td>1.623</td>
<td>−0.6</td>
<td>Basal {0001}{11\bar{2}0}</td>
<td>None</td>
<td>None</td>
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<tr>
<td>Zr</td>
<td>1.593</td>
<td>−2.4</td>
<td>Prismatic {10\bar{1}0}{11\bar{2}0}</td>
<td>Basal {0001}{11\bar{2}0}</td>
<td>Pyramidal {10\bar{1}1}{11\bar{2}0}{11\bar{2}2}{11\bar{2}3}</td>
</tr>
<tr>
<td>Ti</td>
<td>1.588</td>
<td>−2.8</td>
<td>Prismatic {10\bar{1}0}{11\bar{2}0}</td>
<td>Basal {0001}{11\bar{2}0}</td>
<td>Pyramidal {10\bar{1}1}{11\bar{2}0}{11\bar{2}2}{11\bar{2}3}</td>
</tr>
<tr>
<td>Hf</td>
<td>1.581</td>
<td>−3.2</td>
<td>Prismatic {10\bar{1}0}{11\bar{2}0}</td>
<td>Basal {0001}{11\bar{2}0}</td>
<td>Pyramidal {10\bar{1}1}{11\bar{2}0}{11\bar{2}2}{11\bar{2}3}</td>
</tr>
<tr>
<td>Be</td>
<td>1.568</td>
<td>−4.0</td>
<td>Basal {0001}{11\bar{2}0}</td>
<td>Prismatic {10\bar{1}0}{11\bar{2}0}</td>
<td>Pyramidal {10\bar{1}1}{11\bar{2}0}{11\bar{2}2}{11\bar{2}3}</td>
</tr>
</tbody>
</table>

• At high cooling rate from above martensite start temp transform β phase completely into hcp α by diffusionless transformation
• It does not lead to embrittlement but slightly increased strength compared to α titanium
• Two types of martensite
  • Hexagonal α’ martensite- shows needle like fine basket-weave structure
  • Orthorhombic α” martensite- quenching below 900°C, shows good deformability

Ref: - Titanium and Titanium Alloys, C. Leyens and M. Peters, Wiley publication
The mechanics of machining
Chip freeze experiments

Temperature measurement

Chip

Adiabatic shear band

Cutting tool movement

Machining affected surface

Trial version, Process Sensors

Line L
Min: -5.0°C
Max: -30.4°C

A: 2.5°C

D: 26.5°C

B: 9.0°C

C: -26.8°C
Chip microstructure at dry, LN2, elevated temperature machining condition

Dry machined

LN2 cooled

Elevated temperature (350°C)

Shear band size in µm vs Temperature in °C
Increased machining affected zone (MAZ) and material is subjected higher strain rate with increased temperature.

Optical image of chip obtained at 315 rpm feed rate of 0.11 mm/rev at 350°C heating.

Optical image of chip obtained at 315 rpm feed rate of 0.11 mm/rev at 500°C heating.
Electron Back Scatter Diffraction of Machining affected zone

Machined edge

Machine Affected Zone in µm

Temperature in °C

Machine Affected Zone in µm

Temperature in °C
Influence of speed (feed constant 0.097 mm/rev.) on residual stress at Machined edge.
a. Phase quality map

b. Image quality map
c. SEM image
Fracture criteria

- Segmented chips even at low cutting speeds (saw tooth profile)
- Chip segmentation criteria
- Thermoplastic instability
- Initiation and propagation of cracks inside the primary shear zone of the workpiece material

Cockroft and Latham damage criterion: \[ C_i = \int_0^{\varepsilon_f} \sigma \left( \frac{\varepsilon}{\sigma} \right) I. \] \[ [4,5,6] \]

Johnson Cook (JC) fracture model: \[ D = \sum \frac{\Delta \varepsilon}{\varepsilon_f} \] \[ \sigma^* = \frac{\sigma_m}{\sigma_v} \] \[ [7,8,9] \]

where, \( \varepsilon_f = (D_1 + D_2 \exp(D_3 \sigma^*)) (1 + D_4 \ln(\frac{\varepsilon}{\varepsilon_0})) (1 + D_5 \frac{T - T_{room}}{T_{melt} - T})^m \)
## Material Models

**JC Model**

\[
\sigma = (A + B \varepsilon^n) \left( 1 + C \cdot \ln \left( \frac{\dot{\varepsilon}}{\varepsilon_o} \right) \right) \left( 1 - \left( \frac{T - T_{room}}{T_{melt} - T} \right)^m \right)
\]

- Takes into account strain hardening effect, viscosity effect, softening effect.
- Coupling effects of strain rate and temperature absent.
- The parameters fitted to the stress-strain curves (SPHB).

**Modified JC model**

\[
\sigma = \left( A + B \varepsilon^n \left( \frac{1}{\exp(\varepsilon^a)} \right) \right) \left( 1 + C \cdot \ln \left( \frac{\dot{\varepsilon}}{\varepsilon_o} \right) \right) \left( 1 - \left( \frac{T - T_{room}}{T_{melt} - T} \right)^m \right) \left( D + (1 - D) \tanh \left( \frac{1}{(\varepsilon + s)^c} \right) \right)
\]

- Incorporates the strain softening effect.
- Was able to account for segmented chips formation at low cutting speed.
- The above mentioned models do not consider the effect of microstructure during machining.

**Micromechanical Physic based model**

\[
\sigma = (1215 \cdot \varepsilon^{0.06}) + 601.2 \left( 1 - 9.58 \cdot 10^{-5} T \ln \left( \frac{\dot{\varepsilon}}{4.2 \cdot 10^8} \right) \right)^{\frac{4}{5}}^{\frac{3}{4}}
\]

- Flow stress has two parts: Athermal part ($\sigma_a$).
- Thermal part ($\sigma^*$).
- Above critical temperature, gave a constant value of stress for all temperature hence not for machining.

**Modified Micromechanical physics based model**

\[
\sigma = (a \varepsilon^n + b) (c T^2 + dT^* + e) h(\varepsilon, \varepsilon)
\]

- Temperature dependent flow softening.
- Phase change not incorporated.
FEM Simulation

\(a.\) at 23.4 m/min, room temp.

\(b.\) at 91.8 m/min, room temp.
Phase transformation calculation

Temperature distribution
20 deg C (130) To 700 deg C (254)

Beta Phase distribution
8% (0) To 20% (255)
Case Study 2

Aluminum sheet metal forming
Motivation

Large formability variation of same 5754 Al alloy processed through different processes
Alloy composition and processing

<table>
<thead>
<tr>
<th>5754 Alloy</th>
<th>Mg wt%</th>
<th>Mn wt%</th>
<th>Cr wt%</th>
<th>Fe wt%</th>
<th>Si wt%</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC</td>
<td>3.0</td>
<td>0.25</td>
<td>0.01</td>
<td>0.18</td>
<td>&lt;0.10</td>
</tr>
<tr>
<td>TBC</td>
<td>3.1</td>
<td>0.25</td>
<td>&lt;0.01</td>
<td>0.24</td>
<td>&lt;0.10</td>
</tr>
<tr>
<td>TRC-I</td>
<td>2.8</td>
<td>0.01</td>
<td>&lt;0.01</td>
<td>0.25</td>
<td>0.10</td>
</tr>
<tr>
<td>TRC-II</td>
<td>2.9</td>
<td>0.01</td>
<td>&lt;0.01</td>
<td>0.24</td>
<td>0.08</td>
</tr>
</tbody>
</table>
Typical microstructure of various 5754 alloys

- **TBC**
- **DC**
- **TRC-I**
- **TRC-II**

**TOP**

**Centre**
Center-line Segregation

Discontinuous centerline segregation in TRC-II
Two type of second phase particles are present.
Through thickness microstructure variation

<table>
<thead>
<tr>
<th></th>
<th>Intermetallics</th>
<th>Oxides</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Volume fraction</td>
<td>Size (µm)</td>
</tr>
<tr>
<td>DC</td>
<td><img src="image1" alt="Graph" /></td>
<td><img src="image2" alt="Graph" /></td>
</tr>
<tr>
<td>TBC</td>
<td><img src="image5" alt="Graph" /></td>
<td><img src="image6" alt="Graph" /></td>
</tr>
<tr>
<td>TRC - I</td>
<td><img src="image9" alt="Graph" /></td>
<td><img src="image10" alt="Graph" /></td>
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<tr>
<td>TRC - II</td>
<td><img src="image13" alt="Graph" /></td>
<td><img src="image14" alt="Graph" /></td>
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</table>
TRC has lower YS and UTS than TBC or DC
Fractographic investigation (TRC-I)

Microvoid formation at particle clusters
Radioactivity monitoring over a specific region is crucial for nuclear safeguards. A comprehensive analysis of radioactivity levels should be conducted to ensure compliance with international standards. This involves detailed examination and interpretation of the data collected from various monitoring stations.
FE predictions of uniaxial stress-strain behavior

Novelis has higher localization strain than Assan
With in Assan, center region has lower localization strain than top
Correlation of localization strain and Extreme Property Index (EPI)

EPI is identified as a key microstructural attribute
Plastic deformation by slip

Single crystal Experiment

Single crystal Simulation

Polycrystal Experiment
Inverse pole figure maps

DC

TRC-I

Rolling Direction

TBC

TRC-II
TBC has more rolling texture while TRC has more re-crystalization texture.
### Summary

#### Particle distribution

<table>
<thead>
<tr>
<th>Texture component</th>
<th>Macro Texture</th>
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</thead>
<tbody>
<tr>
<td>DC</td>
<td></td>
</tr>
<tr>
<td>TB CC</td>
<td></td>
</tr>
<tr>
<td>TR CC – I</td>
<td></td>
</tr>
<tr>
<td>TR CC – II</td>
<td></td>
</tr>
</tbody>
</table>

#### Rolling Direction

- **Novelis DC**
- **Assan-I**
- **Assan-II**

#### Graphs

- Graph showing stress-strain relationship for different materials.
- Graph illustrating volume fraction of texture components.
Conclusion

Multi-scale Multimodality Microstructure plays a central role in manufacturing processes.

1.) Machined surface quality and performance is a stronger function of microstructure.

2.) In forming particle distribution and texture can work in cross purpose.