Process Modeling of Micro-Cutting Including Strain Gradient Effects

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Presentation Outline

- Characteristics of micro-cutting
- Research objectives
- Numerical modeling of micro-cutting process
- Strain gradient plasticity
- Initial results
- Future work
Typical Characteristics of Micro-Cutting Process

- Very small undeformed chip thickness (1 µm~100 µm)
- Tool edge geometry dimension comparable to undeformed chip thickness.
- Large negative rake angle
- Large shear strain, strain gradient in primary shear zone.

Undeformed chip thickness $t_0$
Size effect in machining

Work material: AISI-1045
Tool geometry: $\alpha = 5^\circ$
Cutting conditions: $U = 420 \, \text{m/min}$
$w = 2.0 \, \text{mm}$

Specific cutting pressure vs. undeformed chip thickness.
Research Objectives

- Develop a computational model to describe the micro-cutting process, taking into account the size effect.
- Predict the stresses, strains, temperatures, cutting forces and residual stresses in the micro-mechanically machined workpiece.
- Experimentally verify model.
Essential Model Capabilities

- Fully coupled thermal-mechanical analysis
- Accurate material flow stress modeling
- Physically-based chip separation criterion
- Adaptive remeshing capability
- Fracture initiation and crack growth
- Friction characteristics
Finite Element Model Configuration
**Strain Gradient Plasticity**

- Classical Plasticity
- Strain gradient Plasticity
- Dislocation Mechanics
- Molecular Dynamics

<table>
<thead>
<tr>
<th>Min. Length</th>
<th>Macroscale</th>
<th>Polycrystal</th>
<th>Discrete Dislocations</th>
<th>Atomistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scale L</td>
<td>O(10^{-3}m)</td>
<td>O(10^{-5}m)</td>
<td>O(10^{-8}m)</td>
<td>O(10^{-10}m)</td>
</tr>
</tbody>
</table>

0.1 μm~10 μm

October 29th, 2002

IAB Meeting for PMRC
Strain Gradient Plasticity

\[ E = \frac{1}{2} \left( F^T \cdot F - 1 \right) \]
Green strain tensor \( E \)

\[ \eta_{ijk} = E_{ik,j} + E_{jk,i} - E_{ij,k} \]
Strain gradient tensor \( \eta \)

\[ \tau = \alpha \mu b \sqrt{\rho_s + \rho_g} \]
\[ \bar{\sigma} = \sigma_y \sqrt{f^2(\bar{\varepsilon}) + l\bar{\eta}} \]
\[ l = 3\alpha^2 \left( \frac{\mu}{\sigma_y} \right)^2 b \]

microscale \( \tilde{\varepsilon}, \tilde{\sigma} \)
mesoscale \( \varepsilon, \eta, \sigma, \tau \)
Strain Gradient vs. Classical Plasticity: Nanoindentation Example

\[ (H/H_0)^2 \]

Finite Deformation Theory of MSG Plasticity

\( \alpha = 0.34 \)

Experiment (McElhaney et al., 1998)

Classical Plasticity

\[ 1/h \, (\mu m^{-1}) \]
### Machining / Indentation Analogy

<table>
<thead>
<tr>
<th>Shear strain</th>
<th>Indentation ( \gamma \approx 0.36 )</th>
<th>Machining ( \gamma \approx 2 \sim 4 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strain gradient</td>
<td>( \eta = 4\gamma / D )</td>
<td>( \eta \approx 4\gamma / t )</td>
</tr>
<tr>
<td>Hardness or Specific force</td>
<td>( H = C'Gb\sqrt{\rho_s + (4\gamma / bD)} )</td>
<td>( F \approx AGb\sqrt{\rho_s + (4\gamma / bt)} )</td>
</tr>
<tr>
<td>Characteristic length Of deformation field</td>
<td>Indentation diameter, ( D )</td>
<td>Undeformed chip thickness, ( t_0 )</td>
</tr>
<tr>
<td></td>
<td>0.1 ( \mu m \sim 10 \mu m )</td>
<td>0.5 ( \mu m \sim 50 \mu m )</td>
</tr>
</tbody>
</table>
Initial Results
Future Work

- Implement strain gradient plasticity in finite element model
- Validate model by micro-/nano-indentation and/or micro-cutting experiment data