Machining Process Modeling and Simulation: Challenges and Unique Capabilities

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Grand Challenge

• To be able to model, simulate, and optimize industrial machining processes without physical experimentation

• Key desirable attributes:
  – Realistic models (3 dimensional)
  – Accurate physics
  – Ability to simulate final part quality
  – Ability to optimize multiple objectives
  – Low computational cost (minutes not hours or days!)
  – Account for sources of uncertainty
Potential Benefits

• Ability to design and optimize complex cutting tool geometries without costly trial-and-error testing.

• Obtain information on parameters that are hard or impossible to measure in-situ, e.g. strain, stress, temperature, forces, microstructure, etc.

• Controlled generation of microstructure and associated mechanical properties, e.g. grain size, crystallographic texture, hardness, etc.

• Enable explicit consideration of manufacturing process effects in computational materials design
Challenges for Different Modeling Approaches

Theoretical Modeling: Many assumptions and boundary/initial conditions

Numerical Modeling: Time consuming, inadequate material models

Empirical Modeling: Segmented observations and limited extendibility

Predictive Modeling

Courtesy: Steven Liang
State-of-the-Art: Numerical Modeling

Temperature

Strain

Cutting Force

Strain Rate

Mises Stress
A Key Challenge: Material Modeling

Material model: \( \sigma = f(\varepsilon, \dot{\varepsilon}, T) \)

SHPB (Split Hopkinson Pressure Bar)

Uniaxial Tensile / Compression Test

Bariani et al. (2001)
Physics-based Material Modeling

Flow Stress

- Strengthening due to Grain Boundaries, $\sigma_G$
  \[ \sigma_G = \frac{k_G}{\sqrt{D}} \]

- Strengthening due to Dislocation Forests, $\sigma_\rho$
  \[ \sigma_\rho = \alpha_\rho \mu b \sqrt{\rho} \]

- Strengthening due to Short Range Barriers, $\sigma_{th}$
  \[ \sigma_{th} = \sigma_0 \left( 1 - \left( \frac{kT}{g_0 \mu b^3 \ln \dot{\epsilon}} \right)^{1/q} \right)^{1/p} \]

- Strengthening due to Dislocation Drag, $\sigma_D$
  \[ \sigma_D = \frac{MB}{\rho_m b^2 \dot{\epsilon}} \]

Dynamic Recrystallization

- Dynamic Recrystallization
  \[ D = D_f + (D_0 - D_f) \tanh \left( \frac{\dot{\epsilon}}{\epsilon} \right)^u \]
  \[ (\Delta \rho)_{DRX} = K(\dot{\epsilon}, T) \left( \frac{2}{D_0} - \frac{2}{D} \right) \]

Hardening & Dynamic Recovery

- Hardening & Dynamic Recovery
  \[ \frac{d\rho}{d\epsilon} = A \sqrt{\rho} - B(\dot{\epsilon}, T) \rho \]
  \[ \rho_{H&DRV} = \left[ \frac{A}{B} + \left( \sqrt{\rho_0} - \frac{A}{B} \right) e^{-\frac{B \epsilon}{2}} \right]^2 \]

\[ \rho = (\Delta \rho)_{DRX} + \rho_{H&DRV} \]

Sponsor: Third Wave Systems, LLC / Department of Energy – IMI, 3-year effort
Sample Validation: OFHC Cu

Experimental data courtesy of C. Saldana (PSU) and S. Chandrasekar (Purdue)

### Sample Result: Microstructure Evolution

<table>
<thead>
<tr>
<th>V_c (m/min)</th>
<th>Grain Size</th>
<th>Dislocation Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>26.6</td>
<td><img src="image1" alt="Grain Size Image" /></td>
<td><img src="image2" alt="Dislocation Density Image" /></td>
</tr>
<tr>
<td>103.3</td>
<td><img src="image3" alt="Grain Size Image" /></td>
<td><img src="image4" alt="Dislocation Density Image" /></td>
</tr>
<tr>
<td>265.7</td>
<td><img src="image5" alt="Grain Size Image" /></td>
<td><img src="image6" alt="Dislocation Density Image" /></td>
</tr>
</tbody>
</table>

**OFHC Cu, Rake Angle = 0°**

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![Georgia Tech Logo](image7)

The George W. Woodruff School of Mechanical Engineering
Hardness Prediction

OFHC Cu
Rake angle: 20°
Cutting speed = 28.2 m/min
Feed = 0.21mm

(Brown et al., 2002)

Experimental data from Elmadagli & Alpas (2003)

OFHC Cu
Rake angle: -5°
Cutting speed = 36 m/min
Feed = 0.25mm

Liu et al., to appear in Procedia CIRP, 2014
Material-Specific Challenges: Ti Alloys

Continuous Chip

Sima & Ozel (2010): Ti-6Al-4V

Segmented Chip

Deng et al. (2012): Copper

Sima & Ozel (2010): Ti-6Al-4V
Limitation of Existing Material Models

**Johnson-Cook (J-C) model (1985)**

\[
\sigma = \left( A + B\varepsilon^n \right) \left( 1 + C\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \left[ 1 - \left( \frac{T - T_r}{T_m - T_r} \right)^m \right]
\]

**Zerilli-Armstrong (Z-A) model (1998)**

\[
\sigma = \sigma_a + B e^{-\left( \beta_0 - \beta_1 \ln \dot{\varepsilon} \right) T + B_0 \varepsilon^n} e^{-\left( \alpha_0 - \alpha_1 \ln \dot{\varepsilon} \right) T}
\]

**Nemat-Nasser (N-N) model (2001)**

\[
\tau = r_0^n + r^0 \left\{ \left[ -\frac{k}{G_0} \ln \dot{\gamma} - \ln \dot{\gamma}_0 + \ln \left[ 1 + a_0 \left( 1 - \left( \frac{T}{T_m} \right)^2 \right) \right] \right] \right\} \left[ 1 + a_0 \left( 1 - \left( \frac{T}{T_m} \right)^2 \right) \right]
\]

*Ti-6Al-4V, Cutting speed: 120m/min; feed: 0.1014mm/rev*
Effect of Failure within Shear Band

\[ \sigma = \left[ \text{constitutive material model} \right] \cdot \left[ F + (1 - F) \cdot \tanh \left( \frac{\varepsilon_c}{\varepsilon} \right)^v \right] \]

- **F**: Controls the asymptotic value of flow stress at large strains.
- **\( \varepsilon_r \)**: Controls the critical strain for initiation of shear band.
- **\( v \)**: Controls the rate of material failure.

Sponsor: Third Wave Systems, LLC / NIST TIP, 3 year effort

*Xue et al. (2002): Ti64*

Liu et al., J. Mat. Proc. Tech., 2013
Ti-6Al-4V Simulation

Plastic Strain:

Temperature:

Note: Zerilli-Armstrong model for Ti-6Al-4V used as the base constitutive model

*Modeling IP licensed to Third Wave Systems, LLC*
Model Validation: Ti-6Al-4V

Liu et al., J. Mat. Proc. Tech., 2013
Analytical Modeling of Tool Performance
(Prof. Steven Liang)

Tool Life Models

Tool Wear Models

Built-up Edge Models

$T_{mod} = T(1 - 0.09 \ln \dot{\varepsilon})$

$T_{mod} < 550K$ and $T_{mod} = T(1 - 0.09 \ln \dot{\varepsilon})$

Aerosol Generation Models

Cutting Fluid Models

rotational speed 145 (rpm)

flow rate (liter/s)

$\dot{\varepsilon} = 0.09$ 

$V (m/min)$

$V_B (\mu m)$

$\text{Aerosol generation rate (A}_{\mu l}/m^3s)$

$\text{Crater (\mu m)}$

$\text{Distance from tool tip (mm)}$

$66 \text{ min}$
Analytical Modeling of Workpiece Performance
(Prof. Steven Liang)
Unique Aspects of GT’s Program

• Nationally and internationally-recognized core competency in precision machining research: 4* faculty members with complementary expertise in modeling and experiments

• Strong track-record in both basic and applied machining research (since early 1990s); strong industry relationships with repeat “customers”

• Dedicated state-of-the-art laboratory facilities for research in precision machining across multiple length scales; one of the few US university labs in this area

• Strong materials research group available for collaboration e.g. in dynamic characterization of materials

• Synergy with national initiatives in advanced manufacturing and materials e.g. NNMIs in Light Weight Metals, Digital Manufacturing, Additive Manufacturing, DARPA Adaptive Vehicle Make effort; Materials Genome Initiative, etc.

*5th member to join in fall 2014
Questions?