Residual Stress Modeling in Machining

Presented by

by

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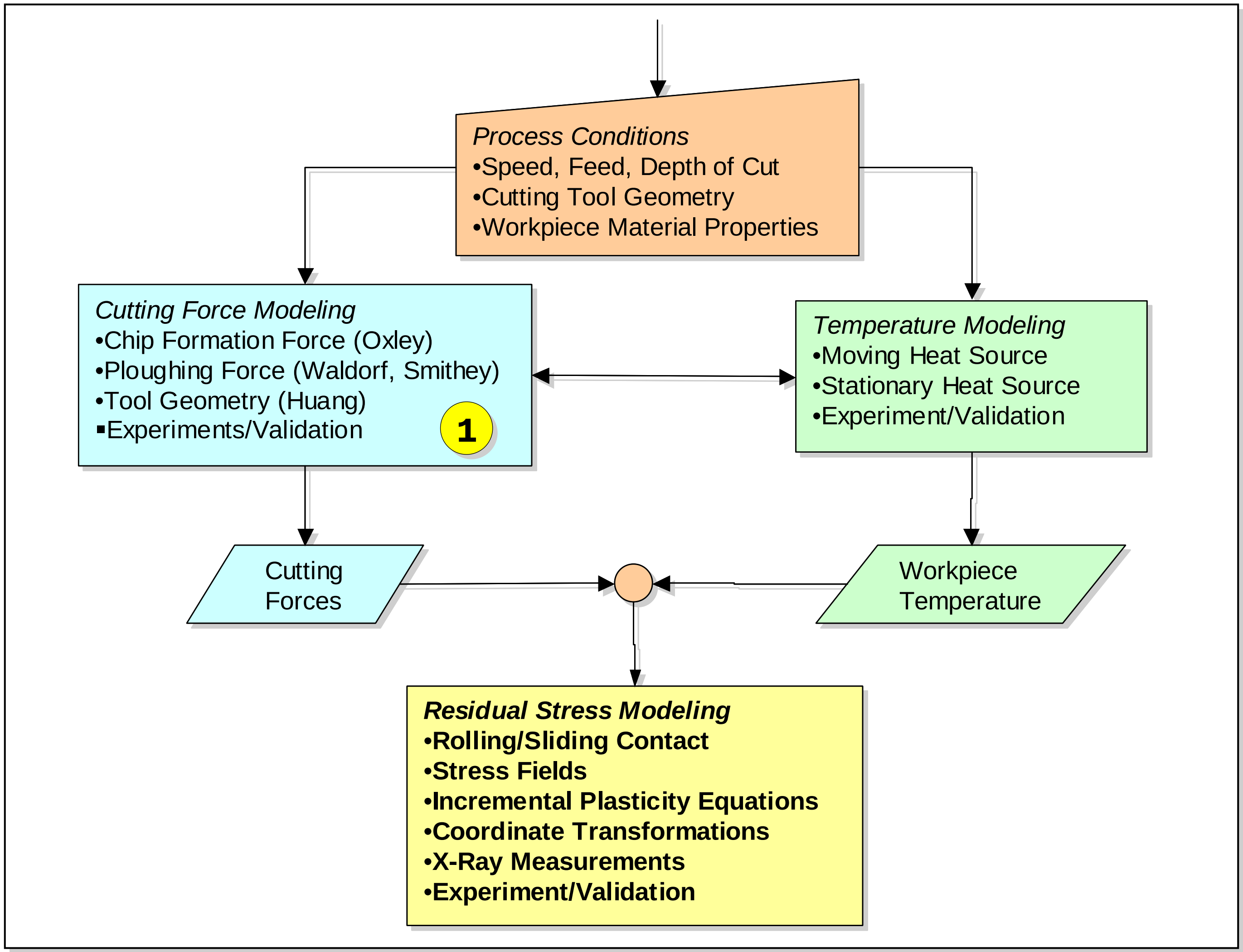
Outline

- Motivation
- Proposed Modeling Method
  - Force modeling
  - Temperature modeling
  - Residual stress modeling
- Questions?

Motivation

- Residual stress affects fatigue life
- Residual stress affects corrosion crack resistance
- Residual stress affects part distortion
- Machining induces residual stress

Physics-Based Modeling Plan

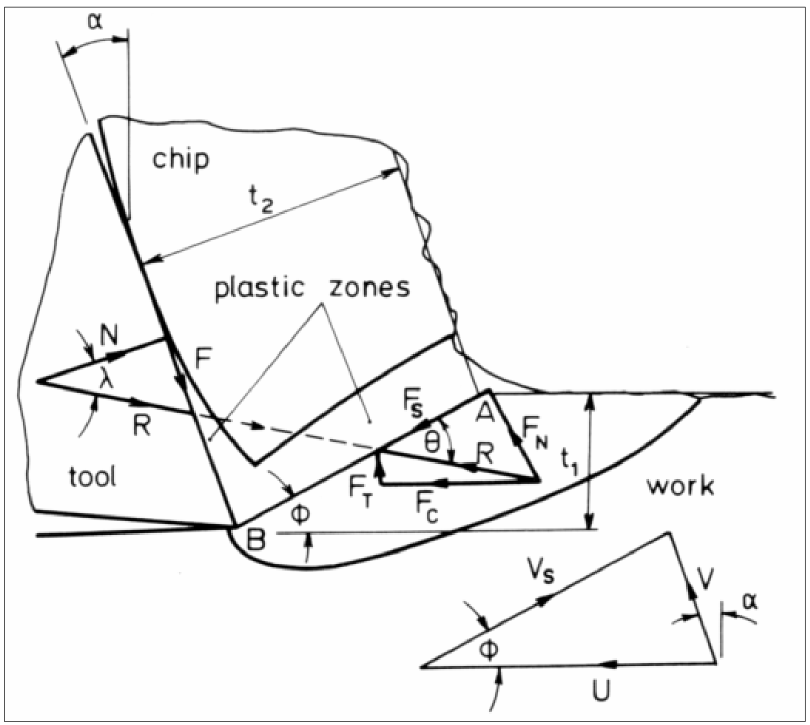


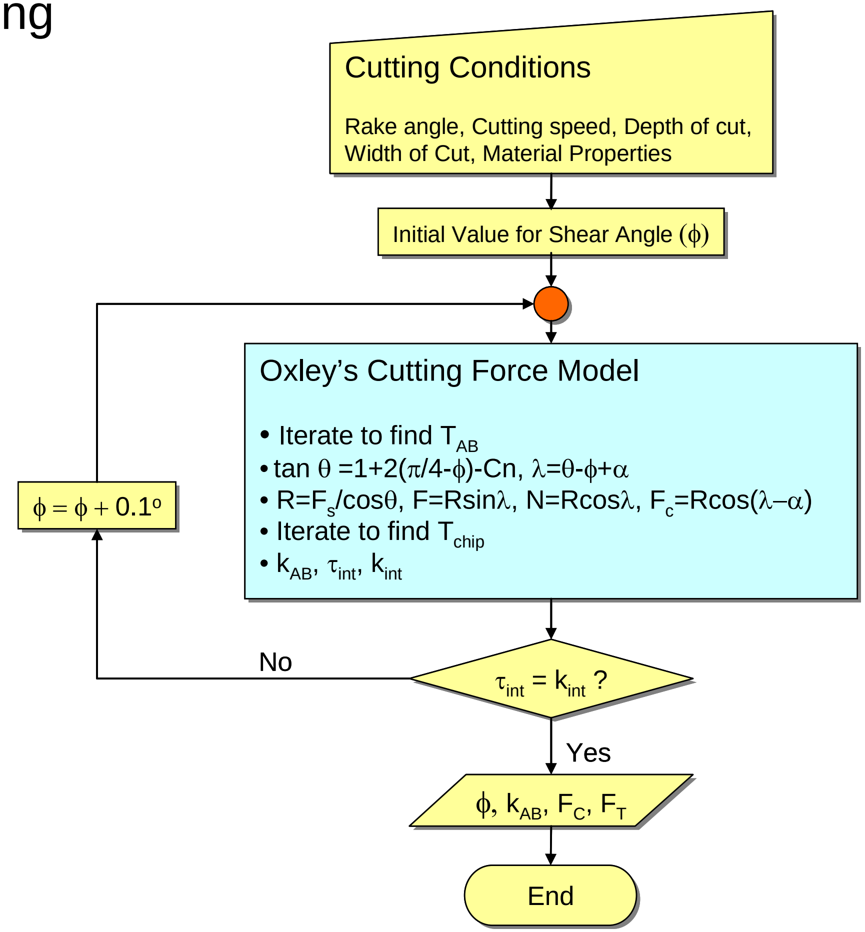
Predicting Cutting Forces

- Sources of Cutting Forces
  - Chip formation forces
  - Ploughing forces
- Classical Models Based on Orthogonal/Oblique Machining
- Geometric Considerations for Non-Orthogonal Processes
  - Side rake angle
  - Back rake angle
  - Tool edge radius
  - Tool nose radius

Predicting Cutting Forces

❖ Cutting Forces for Orthgonal Machining





Predicting Cutting Forces

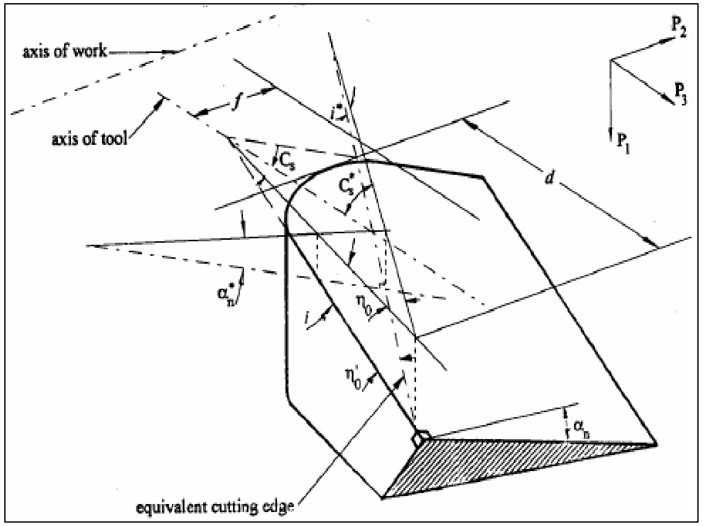
❖ Geometric Transformation for Tool Nose Radius (Wang & Mathew)

- Equivalent oblique transformation

$$F_{cs} = K_n A_c \cos\alpha_n^* + K_f A_c \sin\alpha_n^*$$

$$F_{ts} = K_f A_c \cos\alpha_n^* - K_n A_c \sin\alpha_n^*$$

$$F_R = \frac{F_{cs}\left(\sin i^* - \cos i^* \sin\alpha_n^* \tan\eta_c^*\right) - F_{ts}\cos\alpha_n^* \tan\eta_c^*}{\sin i^* \sin\alpha_n^* \tan\eta_c^* + \cos i^*}$$

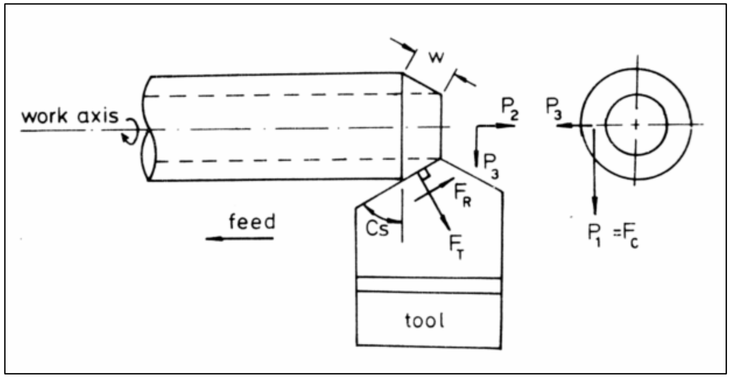


- Force components for non-zero side cutting angle

$$P_1 = F_{cs}$$

$$P_2 = F_{ts}\cos C_S + F_R \sin C_S$$

$$P_3 = F_{ts}\sin C_S - F_R \cos C_S$$



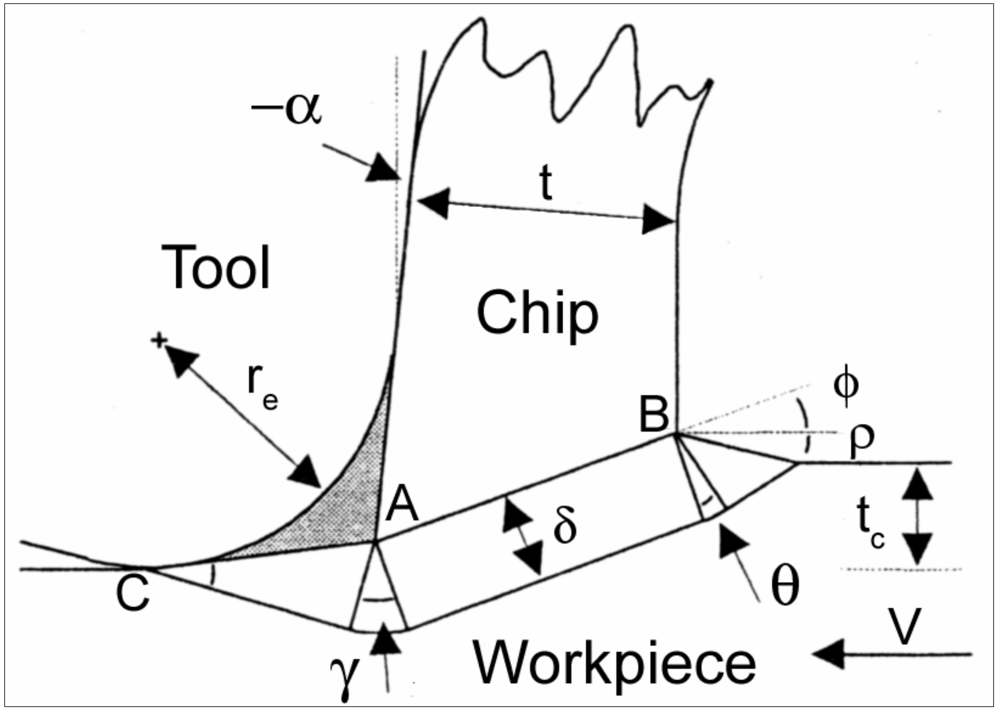
Ploughing Force Prediction

- Ploughing Effects
  - Force contribution due to cutting edge roundness
  - Produces a size effect
- Slip-line field modeling (Waldorf 1999)

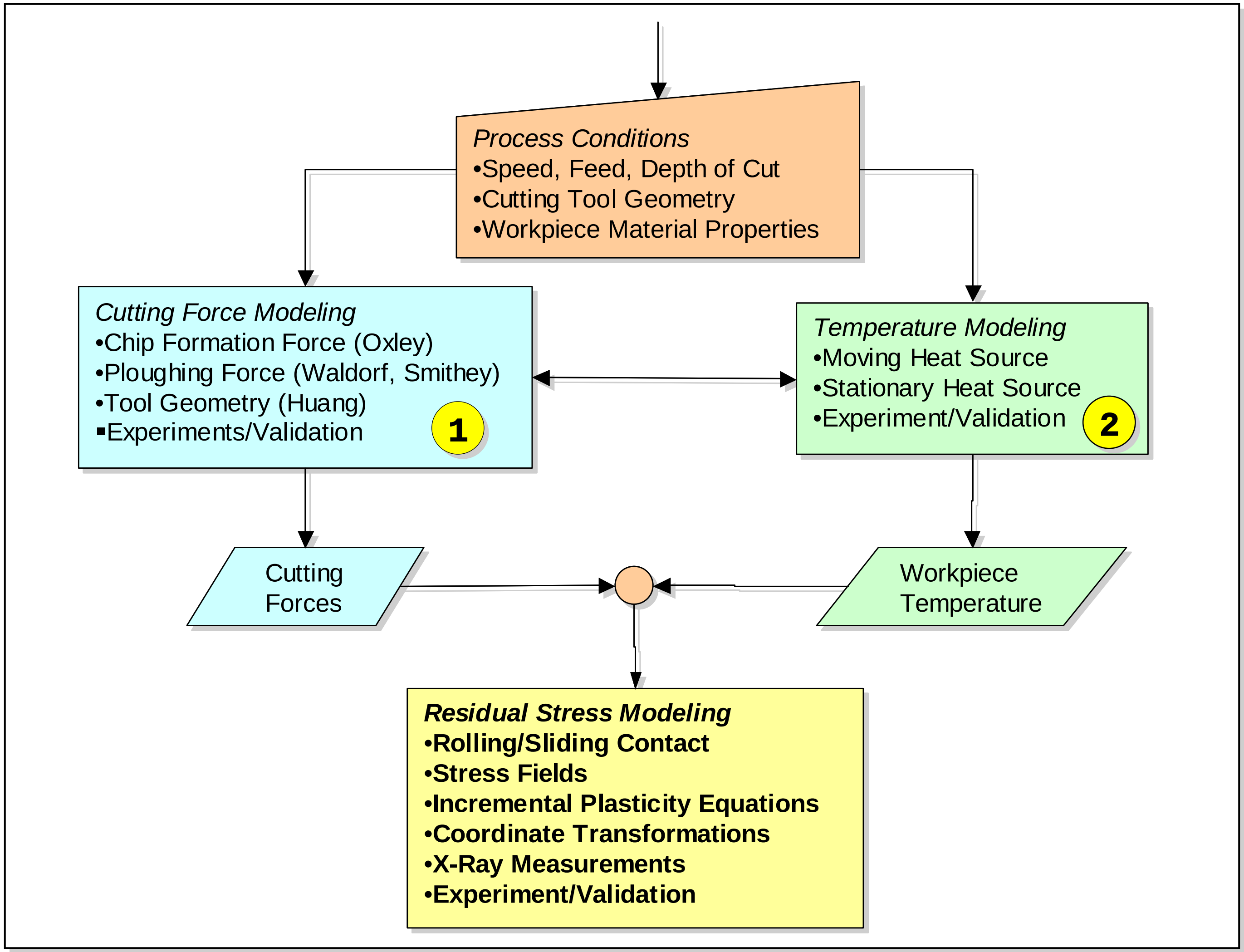
$$P_{cut} = k \cdot w \cdot \begin{bmatrix} \cos(2\eta)\cos(\phi-\gamma+\eta)+ \\ (1+2\theta+2\gamma+\sin(2\eta))\sin(\phi-\gamma+\eta) \end{bmatrix} CA$$

$$P_{thrust} = k \cdot w \cdot \begin{bmatrix} -\cos(2\eta)\sin(\phi-\gamma+\eta)+ \\ (1+2\theta+2\gamma+\sin(2\eta))\cos(\phi-\gamma+\eta) \end{bmatrix} CA$$

$$CA = \frac{\delta}{\sin(\eta)}$$

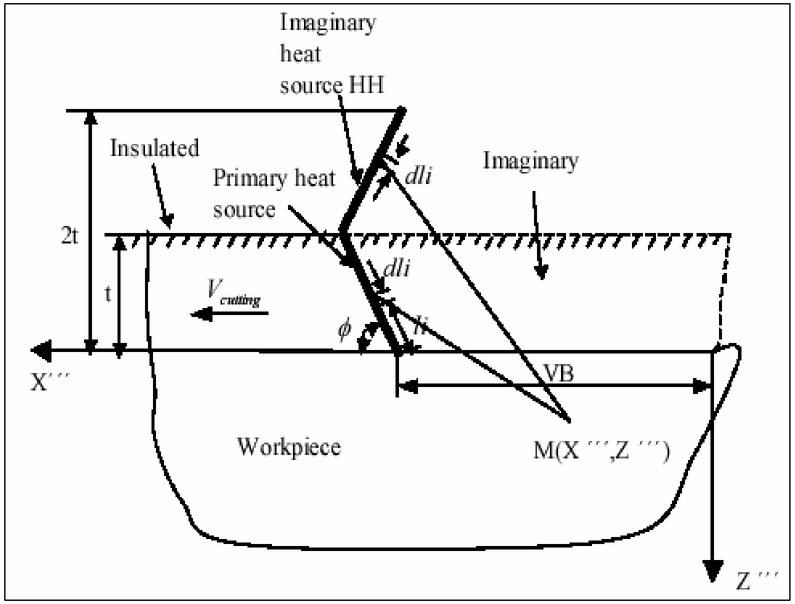


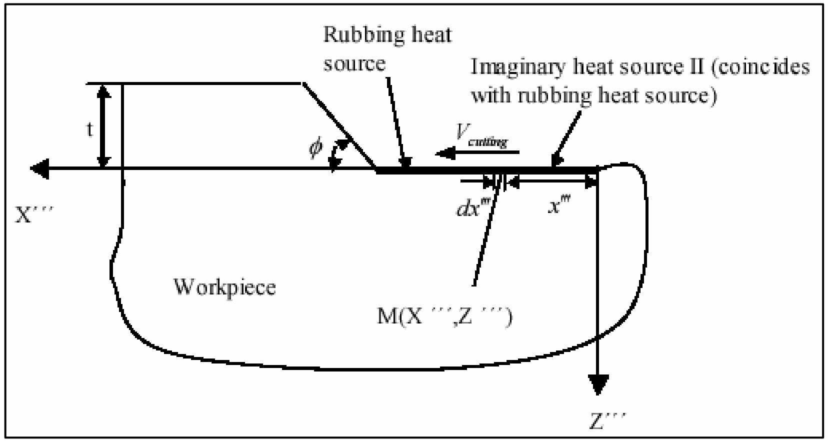
Research Plan



Thermal Modeling

- Thermal Effects
  - Thermal strain
  - Material properties
  - Potential phase change
- Sources of Heat
  - Shear zone
  - Tool edge rubbing
- Previous Research
  - Jaeger's moving heat source
  - Komanduri metal cutting modeling

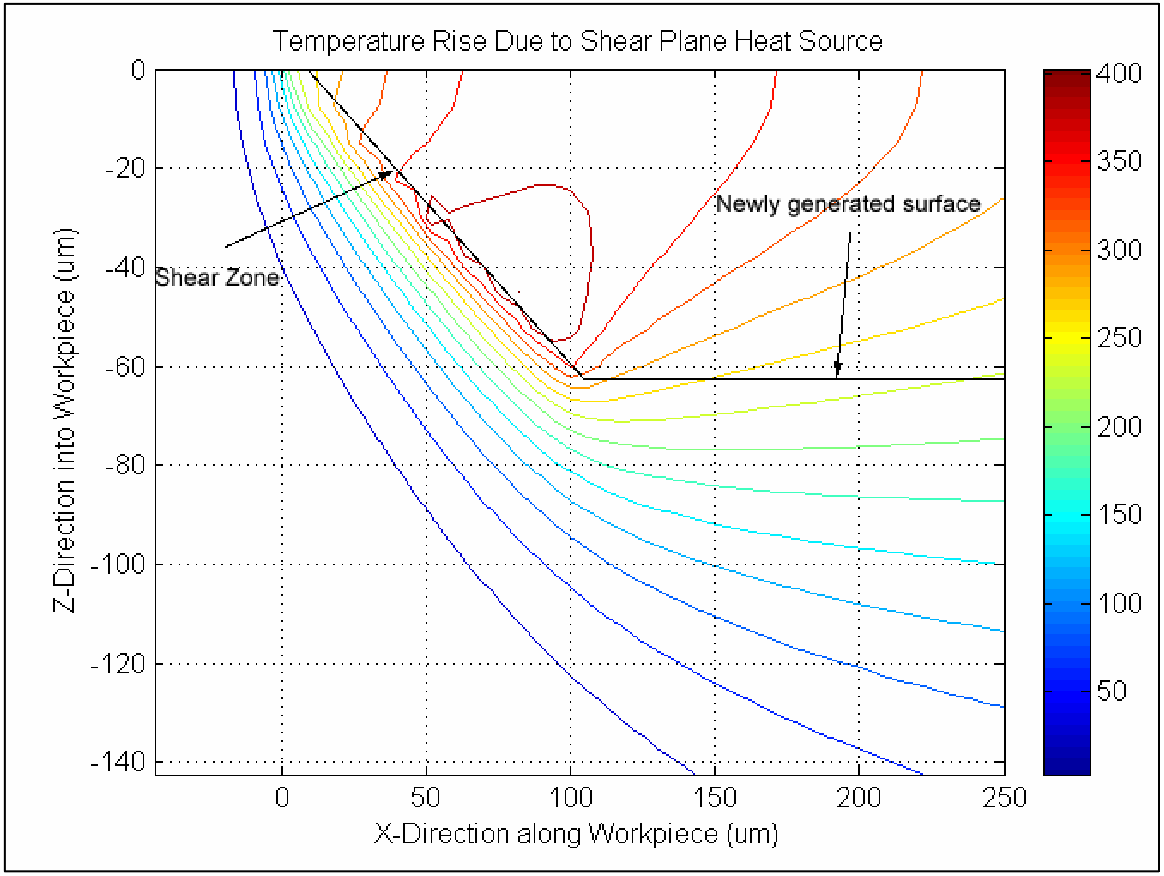




Thermal Modeling

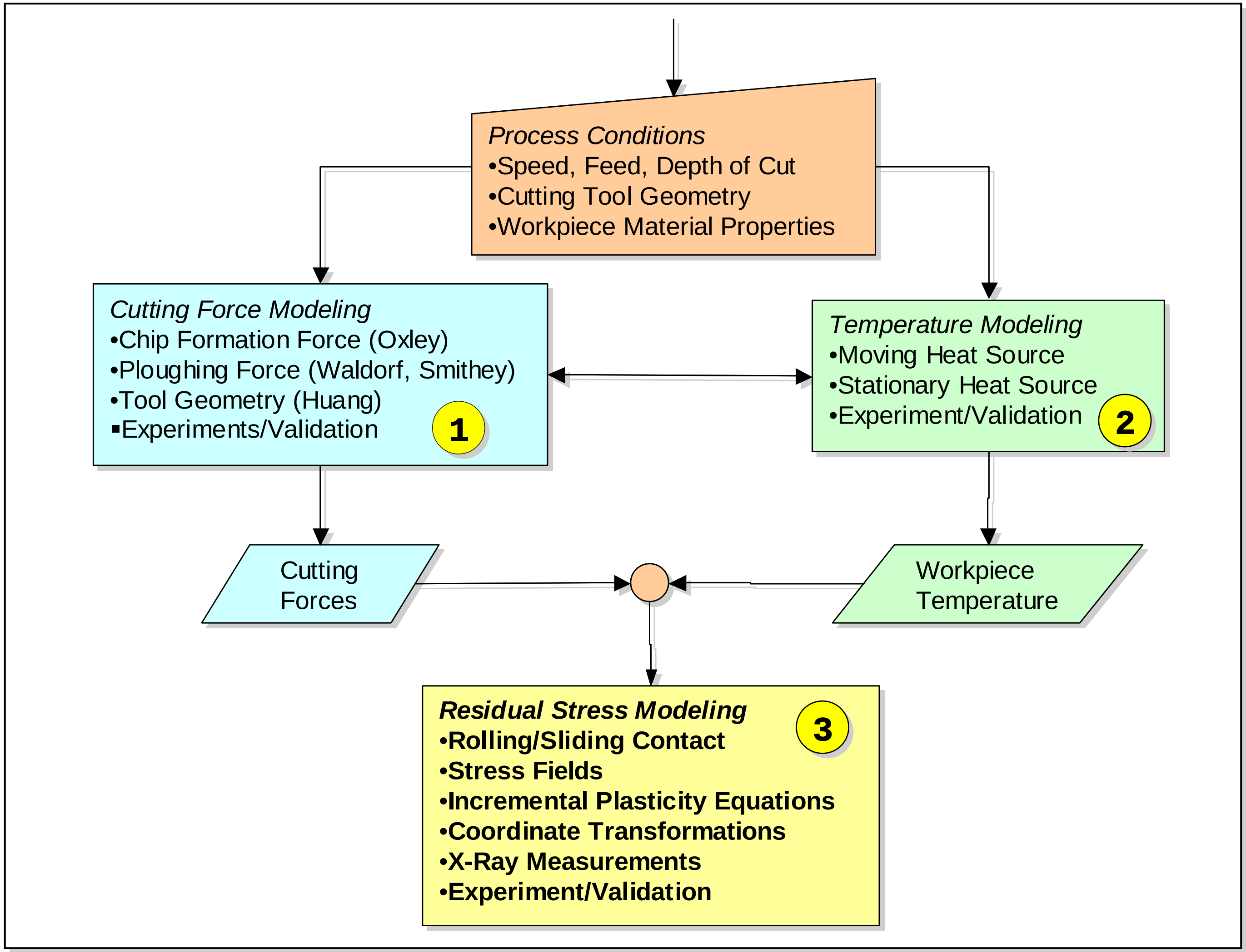
Equation Description	Equation
Temperature Rise Due to Shear	$\theta_{workpiece-shear}(X''', Z''') = \frac{q_{shear}}{2\pi k_{workpiece}} \int_0^L e^{-\frac{(X'''-li\sin\theta-VB)V_{cut}}{2a_{workpiece}}} \left\{ K_0\left[\frac{V_{cut}}{2a_{workpiece}}\sqrt{(VB+li\cos\phi-X''')^2+(Z'''+li\sin\phi)^2}\right] + K_0\left[\frac{V_{cut}}{2a_{workpiece}}\sqrt{(VB+li\cos\phi-X''')^2+(2t+Z'''-li\sin\phi)^2}\right]\right\} dli$
Temperature Rise from Rubbing	$\theta_{workpiece-rubbing}(X''', Z''') = \frac{1}{\pi k_{workpiece}} \int_0^{\backslash VB} B_2(x''') q_{rubbing}(x''') e^{-\frac{(X'''-x''')V_{cut}}{2a_{workpiece}}} K_0\left[\frac{V_{cut}}{2a_{workpiece}}\sqrt{(X'''-x''')^2+(Z''')^2}\right] dx'''$
Temperature Rise in Workpiece	$\theta_{total} = \theta_{shear} + \theta_{rubbing}$

Thermal Modeling



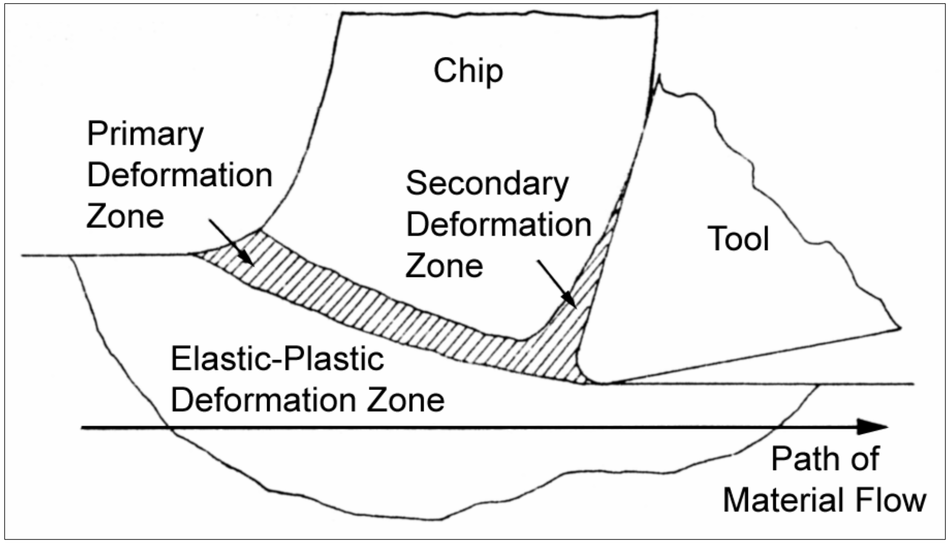
Cutting Speed = 230 ft/min
Shear Angle = 30 deg
Shear Heat Intensity = 11830 J/cm^2-s

Research Plan



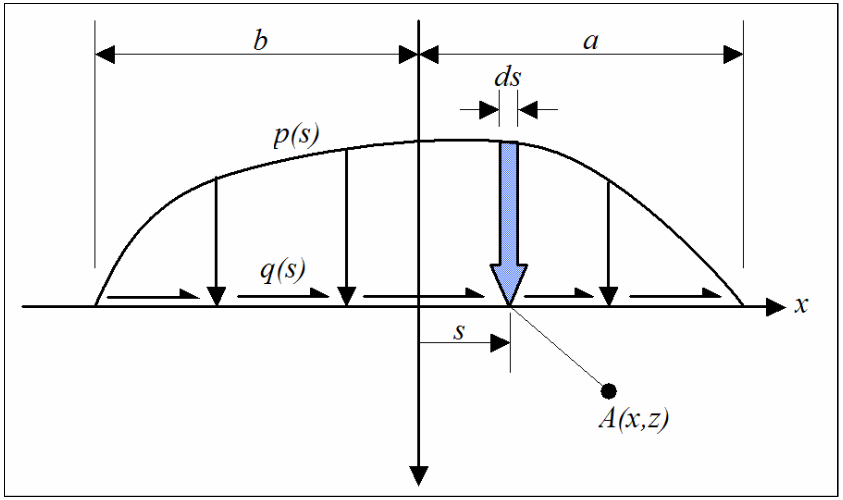
Sources of Stress in Workpiece

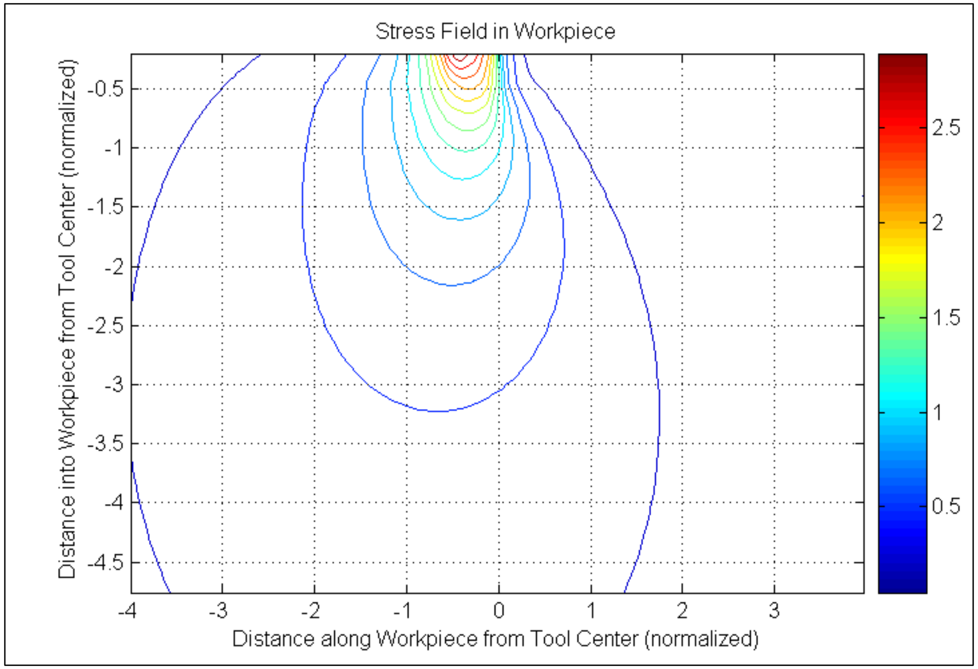
- Primary Deformation Zone
  - Inclined shear stress
  - Inclined normal stress
- Tool Edge Stress
  - Shear stress (rubbing)
  - Normal stress (indentation)



Stress Modeling

❖ Stress Field Due to Normal and Tangential Load





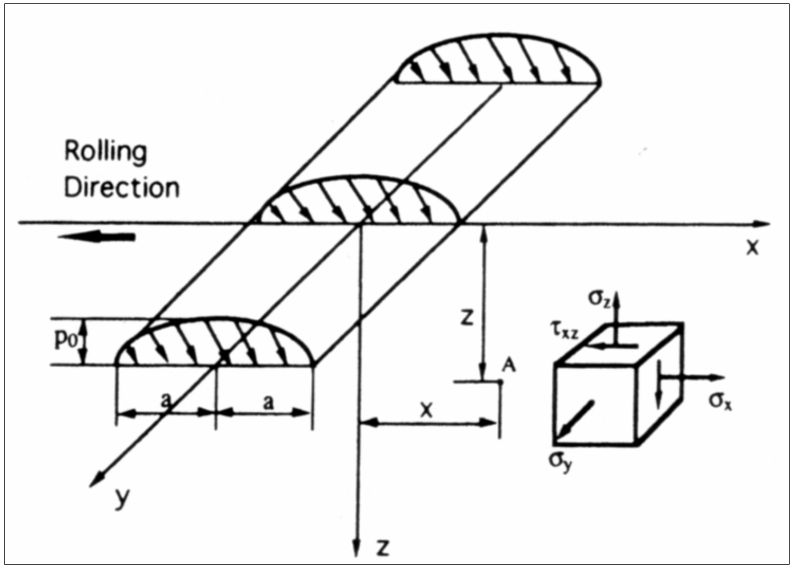
$$\sigma_x = -\frac{2z}{\pi}\int_{-b}^{a}\frac{p(s)(x-s)^2}{\left[(x-s)^2+z^2\right]^2}ds - \frac{2}{\pi}\int_{-b}^{a}\frac{q(s)(x-s)^3}{\left[(x-s)^2+z^2\right]^2}ds$$

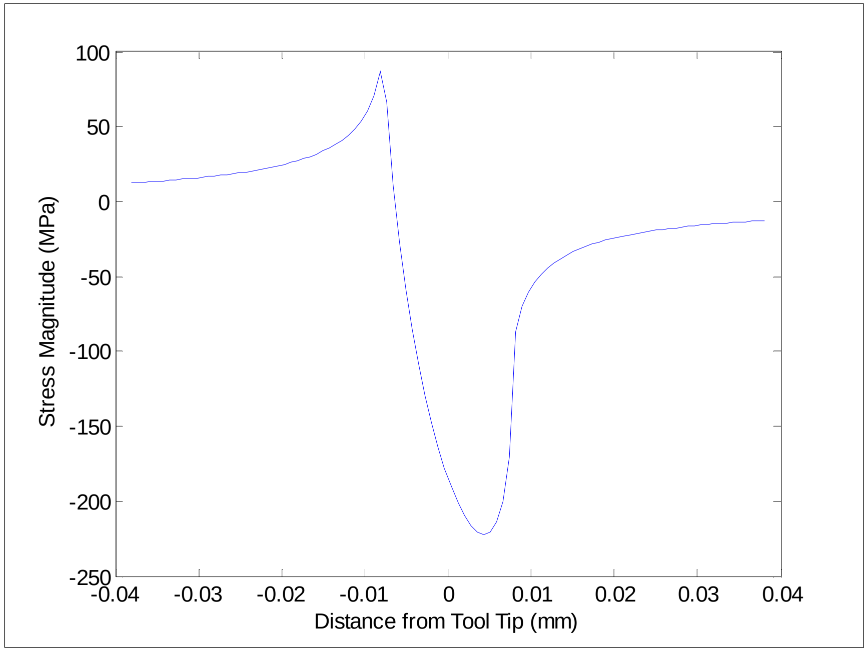
$$\sigma_z = -\frac{2z^3}{\pi}\int_{-b}^{a}\frac{p(s)}{\left[(x-s)^2+z^2\right]^2}ds - \frac{2z^2}{\pi}\int_{-b}^{a}\frac{q(s)(x-s)}{\left[(x-s)^2+z^2\right]^2}ds$$

$$\tau_{xz} = -\frac{2z^2}{\pi}\int_{-b}^{a}\frac{p(s)(x-s)}{\left[(x-s)^2+z^2\right]^2}ds - \frac{2z}{\pi}\int_{-b}^{a}\frac{q(s)(x-s)^2}{\left[(x-s)^2+z^2\right]^2}ds$$

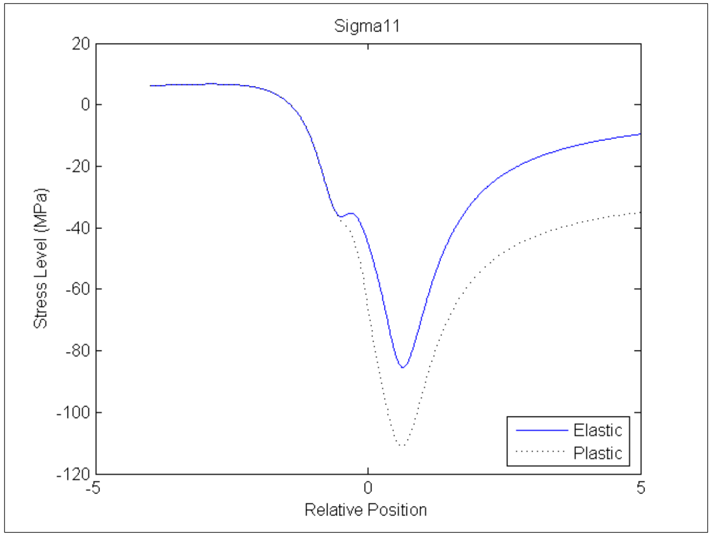
Stress Modeling

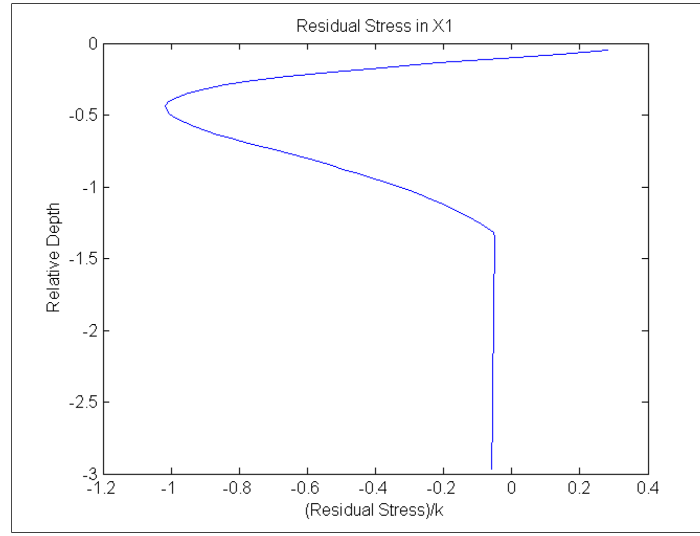
- Rolling Contact Model (Merwin & Johnson, 1963)
  - Stress history experienced by workpiece
  - Total strain assumed equal to elastic strain
  - Elastic-perfectly plastic material behavior
  - Incremental plasticity

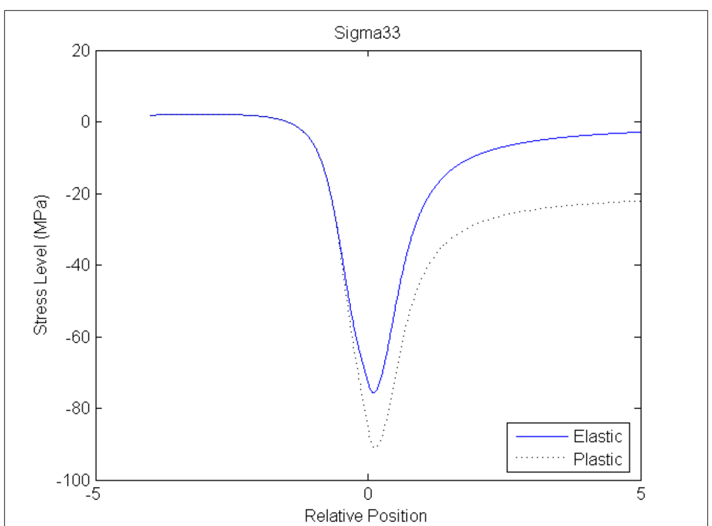


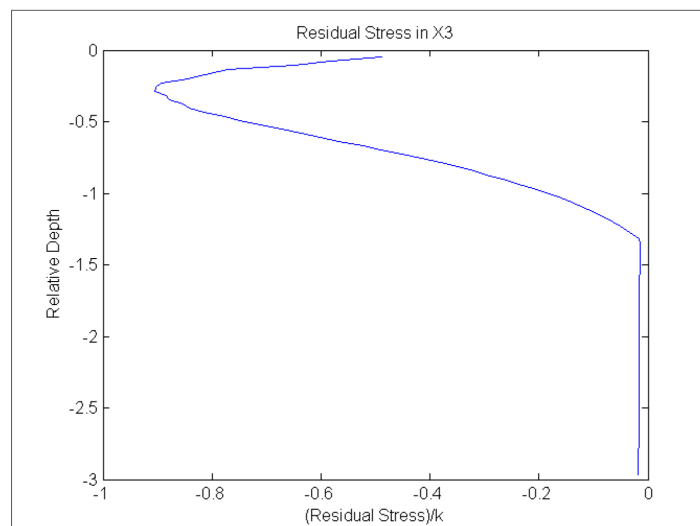


Stress Modeling









McDowell-Hybrid Algorithm

- “Blends” Elements of Other Rolling Contact Algorithms
  - Sehitoglu & Jiang (elastic stress field for all in-plane components)
  - Earlier McDowell & Moyer (no strain in cutting direction)
  - Implements linear kinematic hardening behavior

- Solve for $\dot{\sigma}_{xx}$ and $\dot{\sigma}_{yy}$ simultaneously for stress increments

$$\begin{aligned}\dot{\varepsilon}_{xx} &= \frac{1}{E}\left[\dot{\sigma}_{xx} - \nu\left(\dot{\sigma}_{yy} + \dot{\sigma}^*_{zz}\right)\right] + \alpha\Delta T + \frac{1}{h}\left(\dot{\sigma}_{xx}n_{xx} + \dot{\sigma}_{yy}n_{yy} + \dot{\sigma}^*_{zz}n_{zz} + 2\dot{\tau}^*_{zz}n_{xz}\right)n_{xx} \\ &= \Psi\left(\frac{1}{E}\left[\dot{\sigma}^*_{xx} - \nu\left(\dot{\sigma}_{yy} + \dot{\sigma}^*_{zz}\right)\right] + \alpha\Delta T + \frac{1}{h}\left(\dot{\sigma}^*_{xx}n_{xx} + \dot{\sigma}_{yy}n_{yy} + \dot{\sigma}^*_{zz}n_{zz} + 2\dot{\tau}^*_{zz}n_{xz}\right)n_{xx}\right)\end{aligned}$$

$$\dot{\varepsilon}_{yy} = \frac{1}{E}\left[\dot{\sigma}_{yy} - \nu\left(\dot{\sigma}_{xx} + \dot{\sigma}^*_{zz}\right)\right] + \alpha\Delta T + \frac{1}{h}\left(\dot{\sigma}_{xx}n_{xx} + \dot{\sigma}_{yy}n_{yy} + \dot{\sigma}^*_{zz}n_{zz} + 2\dot{\tau}^*_{zz}n_{xz}\right)n_{yy} = 0$$

- Increments of $\dot{\sigma}_{zz}$ and $\dot{\tau}_{xz}$ are from the elastic solution

Supporting Equations

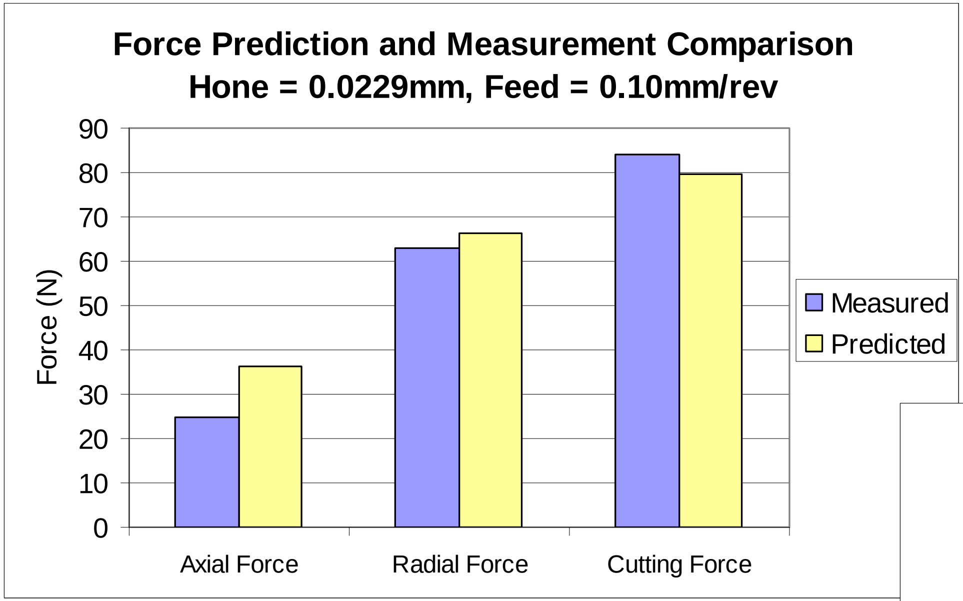
Equation Description	Equation
Plastic strain rate (normality flow rule)	$\dot{\varepsilon}_{ij}^{p} = \frac{1}{h}\left\langle \dot{S}_{kl} n_{kl} \right\rangle n_{ij}$
Deviatoric stress	$\dot{S}_{ij} = \dot{\sigma}_{ij} - \frac{1}{3}\delta_{ij}\dot{\sigma}_{kk}$
Components of unit normal in plastic strain rate direction (on the yield surface)	$n_{ij} = \frac{S_{ij} - \alpha_{ij}}{\sqrt{2}k}$
Von Mises yield surface	$f = \frac{1}{2}\left(S_{ij} - \alpha_{ij}\right)\left(S_{ij} - \alpha_{ij}\right) - k^2 = 0$
Linear kinematic hardening rule	$\dot{\alpha}_{ij} = \left\langle \dot{S}_{kl} n_{kl} \right\rangle n_{ij}$

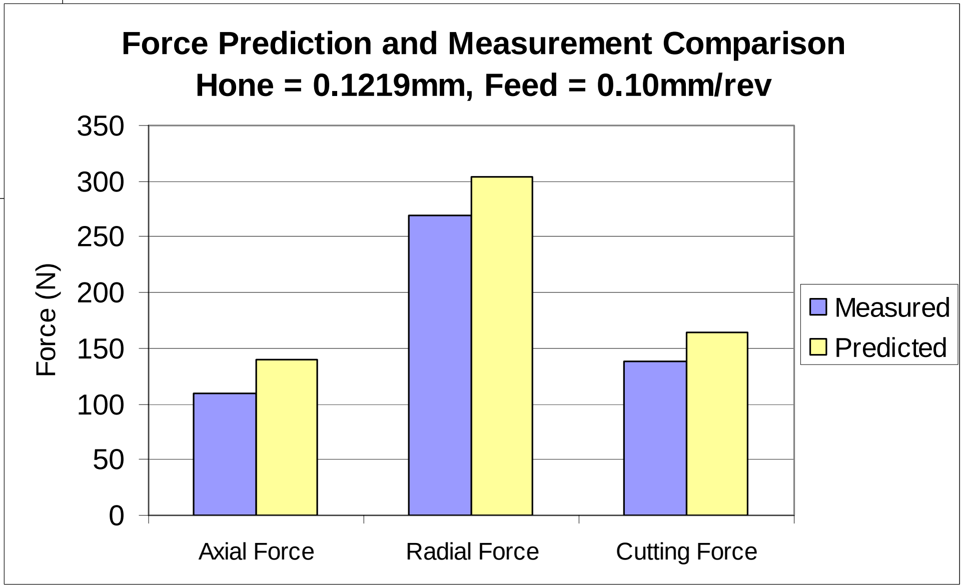
Sample Results

- Thiele & Melkote (1999)

Turning Parameter	Value
Material	AISI 52100 HRC 57
Tool	TNGA-432 KD050 (Low content CBN)
Tool Holder	DTGNL-164D
Tool Nose Radius	0.813 mm
Tool Edge Hone Radius	0.0229mm, 0.1219mm
Cutting Speed	121.9 m/min
Feed	0.11 mm/rev
Depth of Cut	0.254 mm

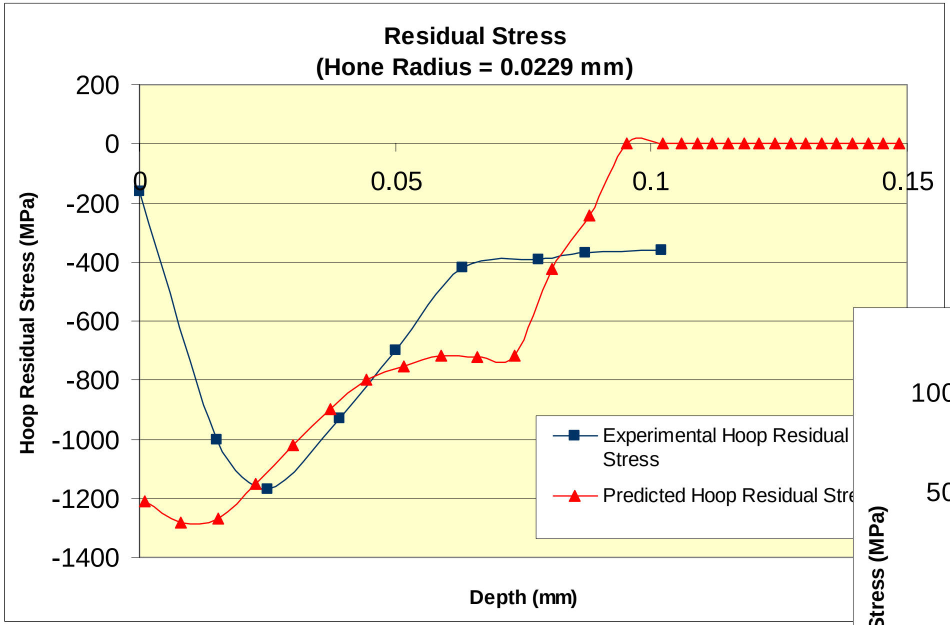
Sample Force Prediction Results

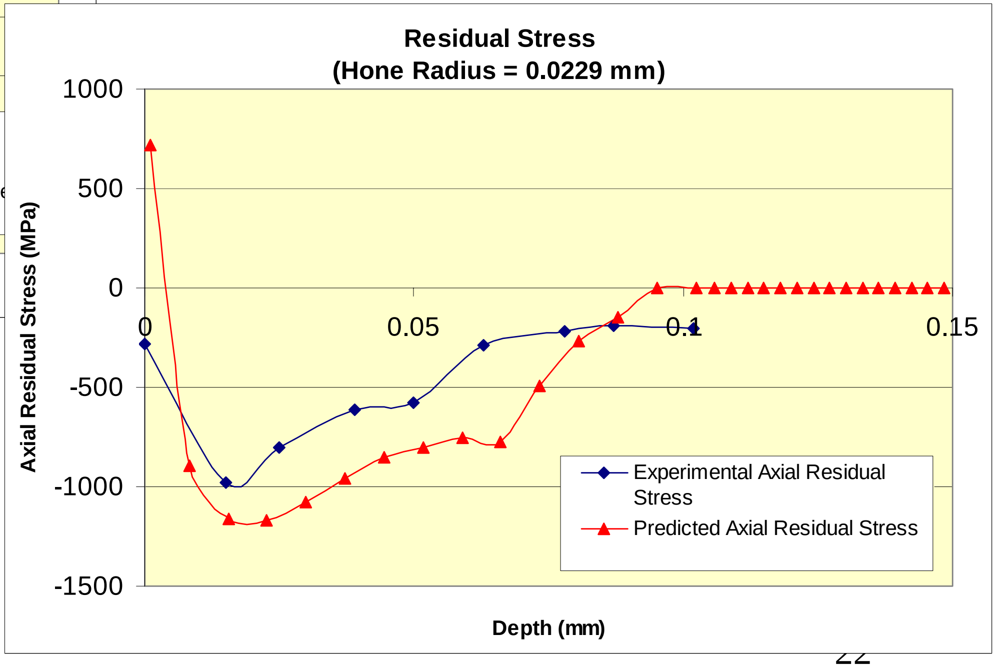




Sample Results

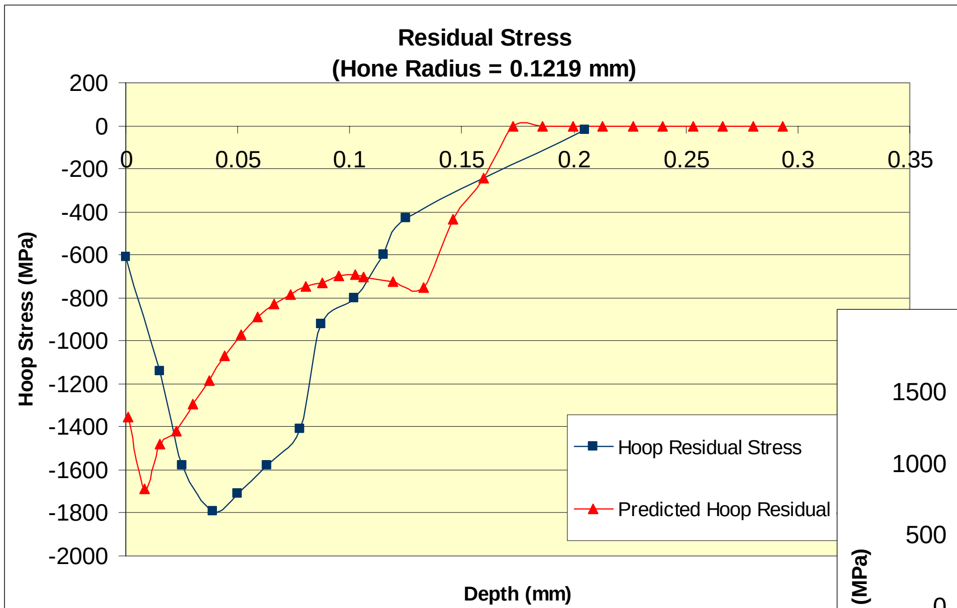
❖ Thiele & Melkote (1999)

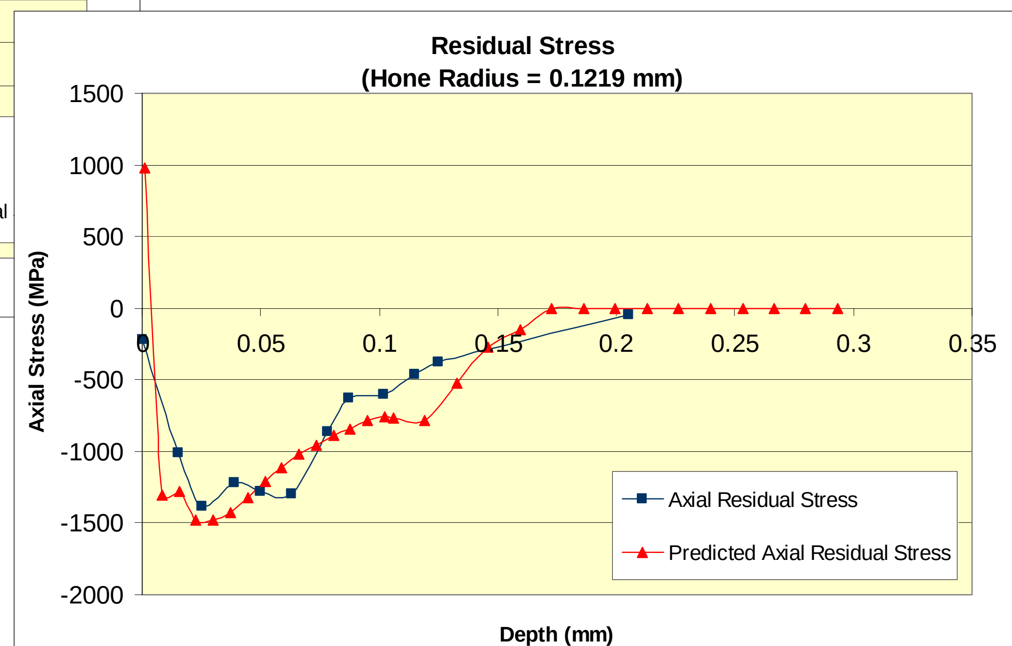




Sample Results

- Thiele & Melkote (1999)

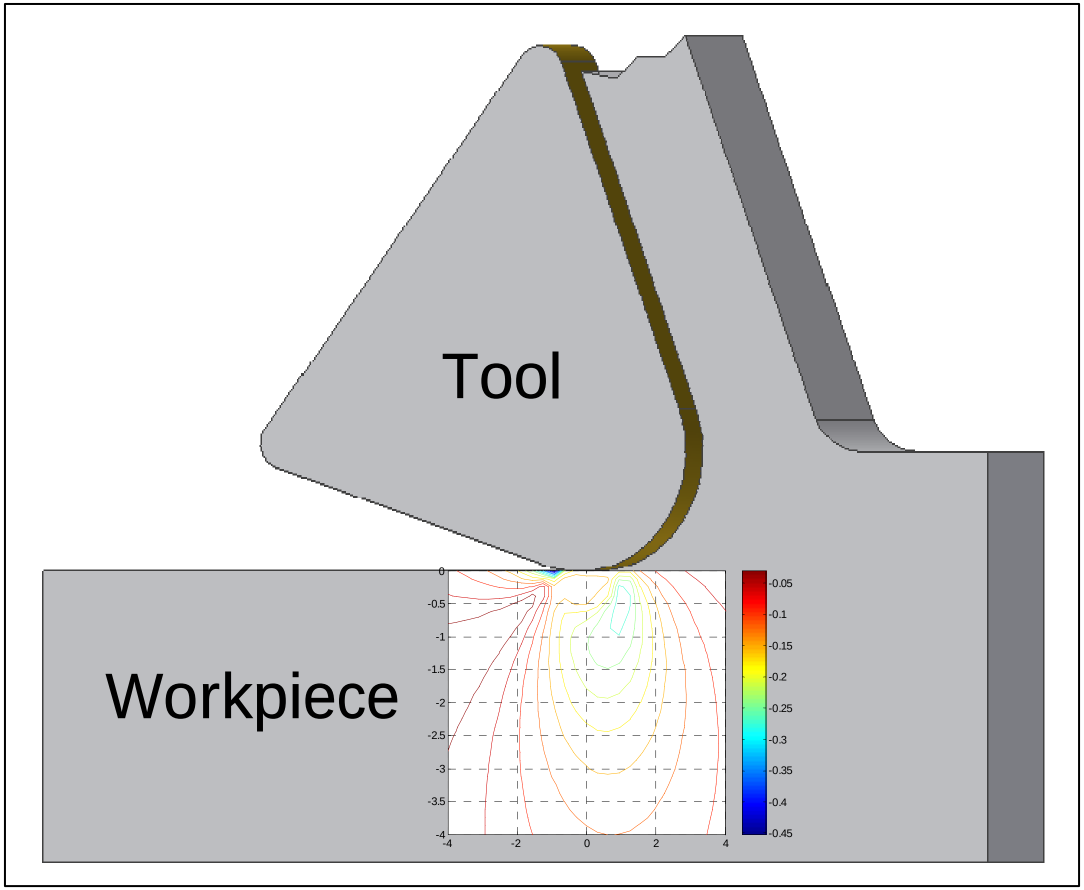




Summary

- Model predicts cutting forces closely
- Model predicts magnitude of residual stresses well
- Model predicts depth of penetration of residual stresses well

Questions?


Tool
Workpiece
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4
-2
0
2
4
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
-0.35
-0.4
-0.45