COMPENSATION OF TOOL FORCES IN SMALL DIAMETER END MILLS

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• BACKGROUND
  – Tool Diameter less than 1 mm
  – Length from 1-12 mm
  – Needed to create small features in hard steel
SCOPE

- DEVELOP TOOL FORCE MODEL
- DEVELOP TOOL DEFLECTION MODEL
- CREATE COMPENSATION TECHNIQUE
CUTTING/THRUST FORCES
• DRESCHER/ARCONA MODEL
  – Cutting and Thrust forces (friction)
  – Function of tool rotation angle
  – Function of tool geometry

\[
F_c = \frac{HA_c}{3} \left( \frac{\cot \phi}{\sqrt{3}} + 1 \right) + \mu_f A_f \left( 0.62 H \sqrt{\frac{43H}{E}} \right)
\]

\[
F_t = \mu \left[ \frac{HA_c}{3} \left( \frac{\cot \phi}{\sqrt{3}} + 1 \right) \right] + A_f \left( 0.62 H \sqrt{\frac{43H}{E}} \right)
\]
TOOL FORCE COMPONENTS

Local chip thickness

Width of wear land

Up Feed/flute

Cross Feed

Depth of cut

Section A-A
• HIGH SPEED MILL
  – 60,000 rpm
  – Mounted on DTM
  – Position resolution less than 10 nm

• 3-AXIS LOAD CELL
  – X, Y, Z forces
  – Average force over several rotations
FORCE COMPARISON

Transformation

\[ r, \theta, z \rightarrow x, y, z \]

Compare

\[ F_{\text{cutting}} \text{ and } F_{\text{thrust}} \]

Force, N

angle, deg

\[ F_x, F_y, F_z \]

Force, N

angle, deg

x, y, z data
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TOOL FORCES

Upfeed = 10 µm/flute
Depth = 25 µm
Speed = 40,000 rpm

Tool rotation angle, degrees

Force, N

Fx
Fx_exp
Fy
Fy_exp
Fz
Fz_exp
TOOL FORCES

Upfeed = 25 µm/flute
Depth = 100 µm
Speed = 10,000 rpm

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• TOOL DEFLECTION EXPERIMENTS
  – Slot with increasing depth
  – Thrust force reduces depth of cut
  – Stiffness depends on tilt of tool
50 deg tilt (no compensation)

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- Measured depth, µm
- Modeled Depth, µm
- Desired Depth, µm

Depth of Groove, µm vs. Distance, mm
50 deg tilt (compensation)

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![Graph showing measured depth, modeled depth, and desired depth vs distance. The graph includes a legend for measured depth, modeled depth, and desired depth.]
COMPENSATION EXPERIMENT

• Cut 0.5 mm deep groove with 1.5 mm radius ball end mill
• Remove 0.1 mm using 0.4 mm radius ball mill (sweep angle ± 50 deg)
• Compensate for tool deflection in y-z plane
TOOL FORCE DIRECTIONS
## Groove with Short Tool

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<th>Sweep Angle (deg)</th>
<th>Error (mm)</th>
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**Legend:**
- Blue: Measured Groove SA
- Green: Uncompensated Deflection Model
- Red: Measured Groove NCS
Groove - Extra Long Tool

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Error (mm) vs. Sweep Angle (deg)

- Measured Groove NCXL
- Uncompensated Deflection Model
- Measured Groove XLA
Compensated Groove
Extra Long Tool

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![Graph showing error vs sweep angle for Measured Groove NCXL, Measured Groove XLA, and Compensated Data.](Image)
Best Fit Radii (1.6 mm)

Error in the best-fit radius to the machined groove, mm

Tool Stiffness, N/mm

- Uncompensated Error, mm
- Compensated Error, mm
CONCLUSIONS

• CUTTING FORCES ARE PREDICTABLE AND REPEATABLE

• TOOL DEFLECTIONS CAN BE CALCULATED AND COMPENSATED

• OPEN-LOOP MODEL CAN BE USED TO IMPROVE THE SHAPE OF SMALL FEATURES

• LIMITATIONS INVOLVE TOOL SHAPE AND TOOL WEAR