COMPENSATION OF TOOL FORCES IN SMALL DIAMETER END MILLS

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Miniature Milling Tools

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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

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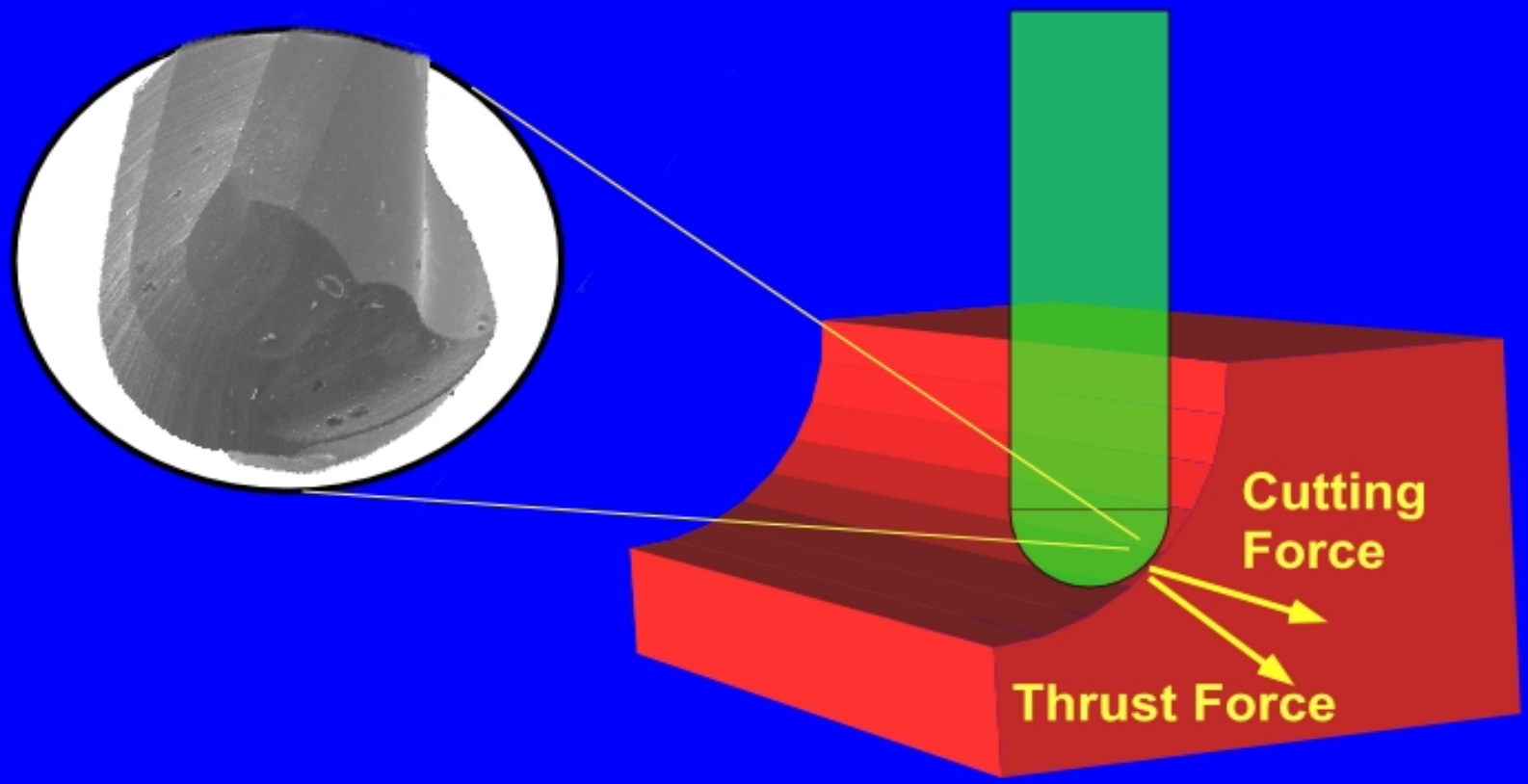

TOOL FORCE MODEL

- DRESCHER/ARCONA MODEL
  - Cutting and Thrust forces (friction)
  - Function of tool rotation angle
  - Function of tool geometry

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

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

TOOL FORCE COMPONENTS

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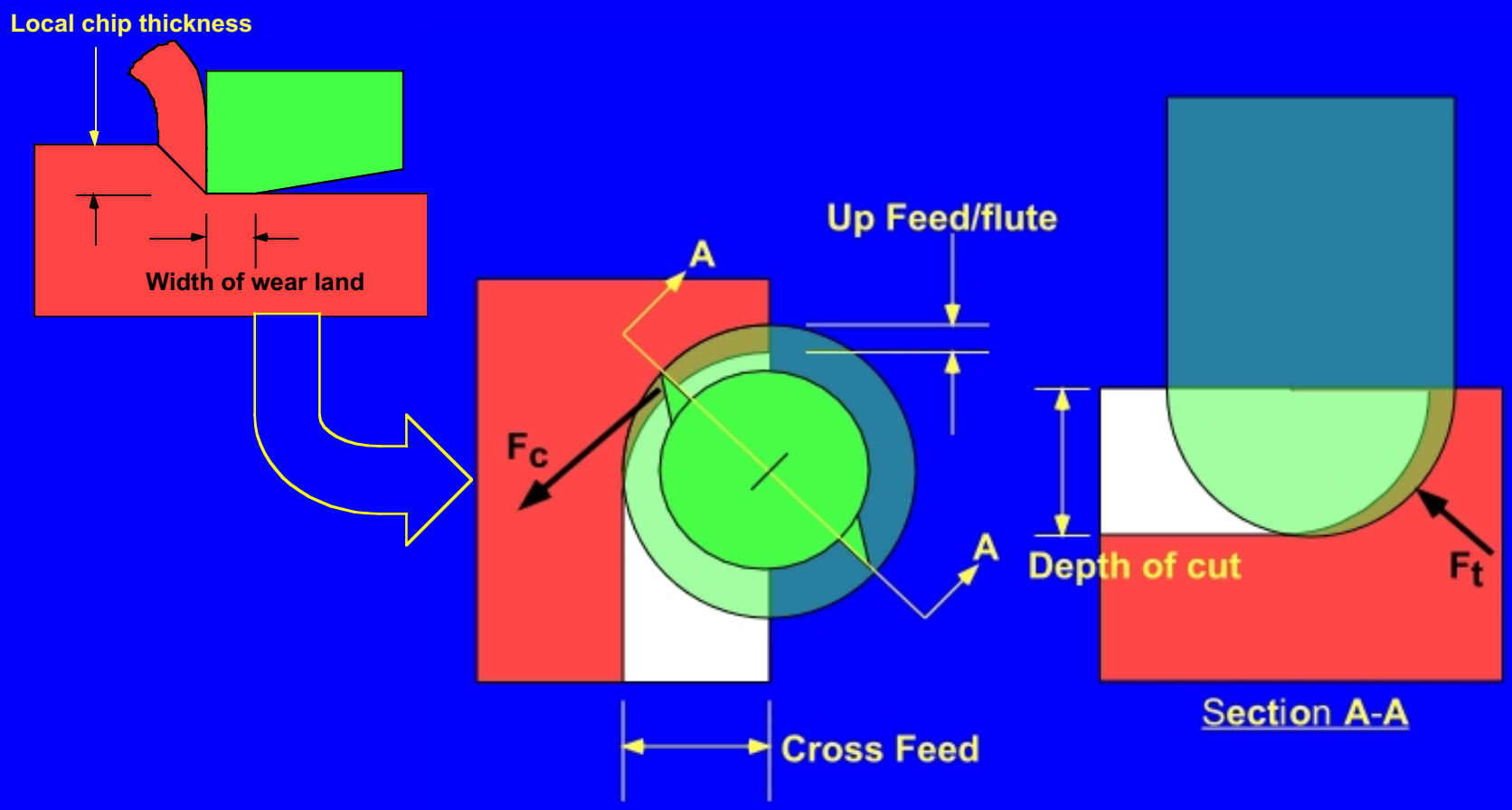

MEASURE TOOL FORCE

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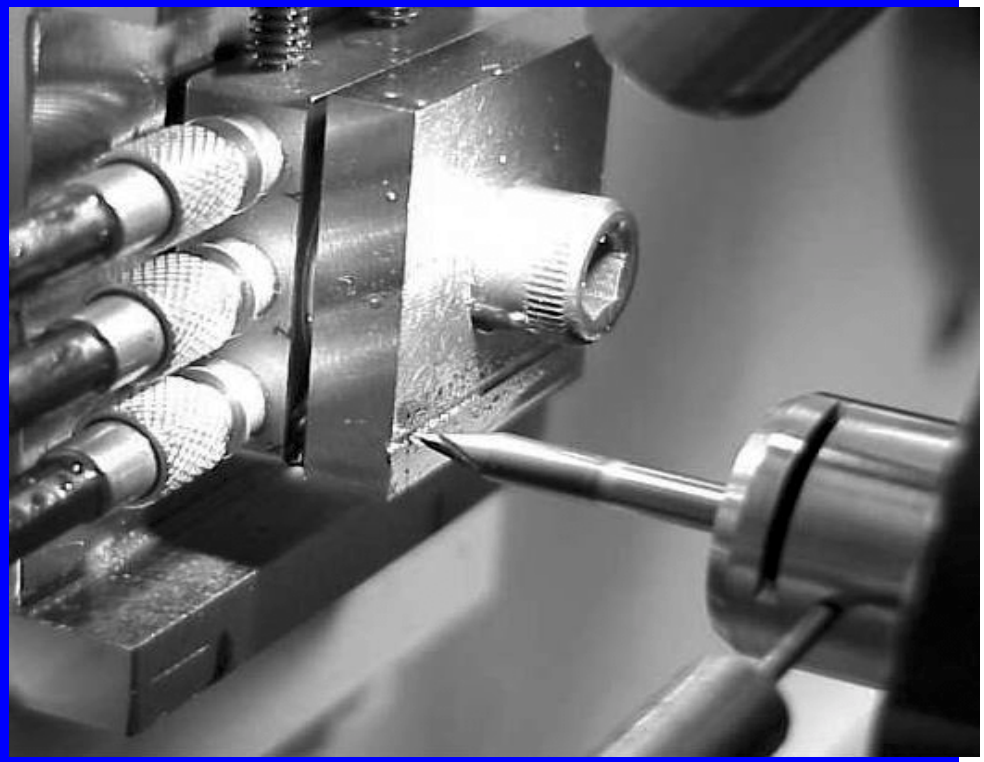
- **HIGH SPEED MILL**
  - 60,000 rpm
  - Mounted on DTM
  - Position resolution less than 10 nm
- **3-AXIS LOAD CELL**
  - X,Y, Z forces
  - Average force over several rotations



FORCE COMPARISON

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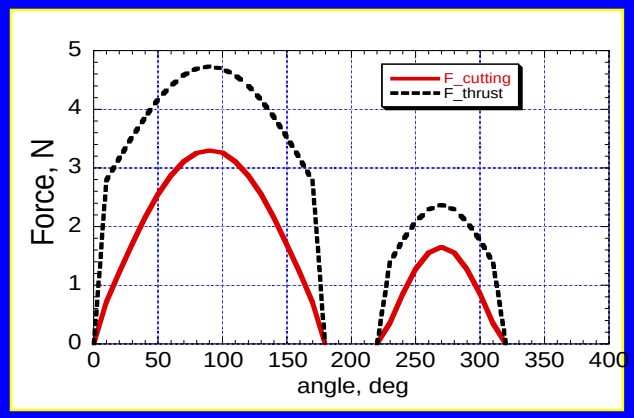
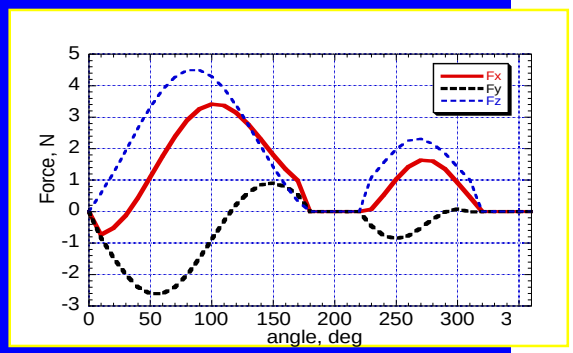
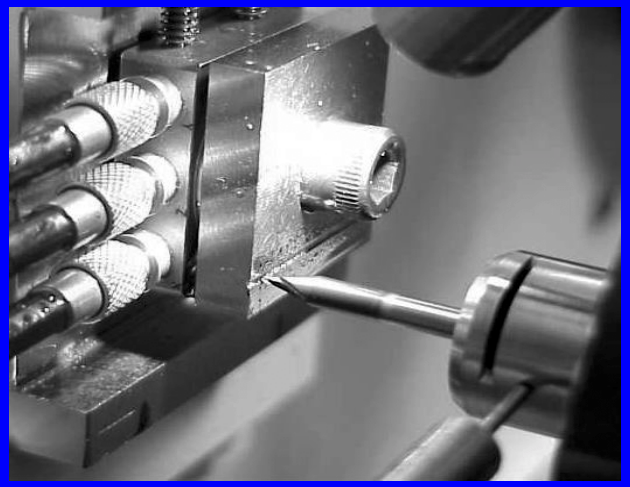


Transformation

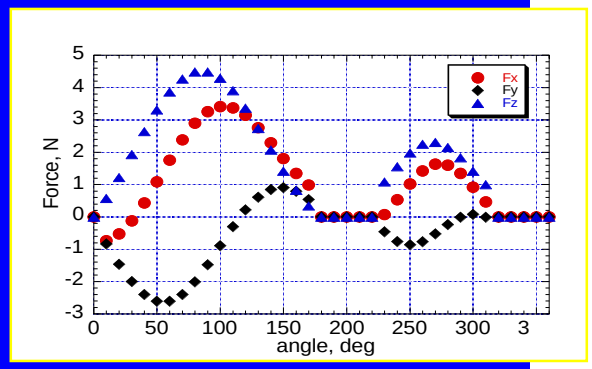
r,θ,z → x,y,z



Compare



x,y,z data →



TOOL FORCES

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

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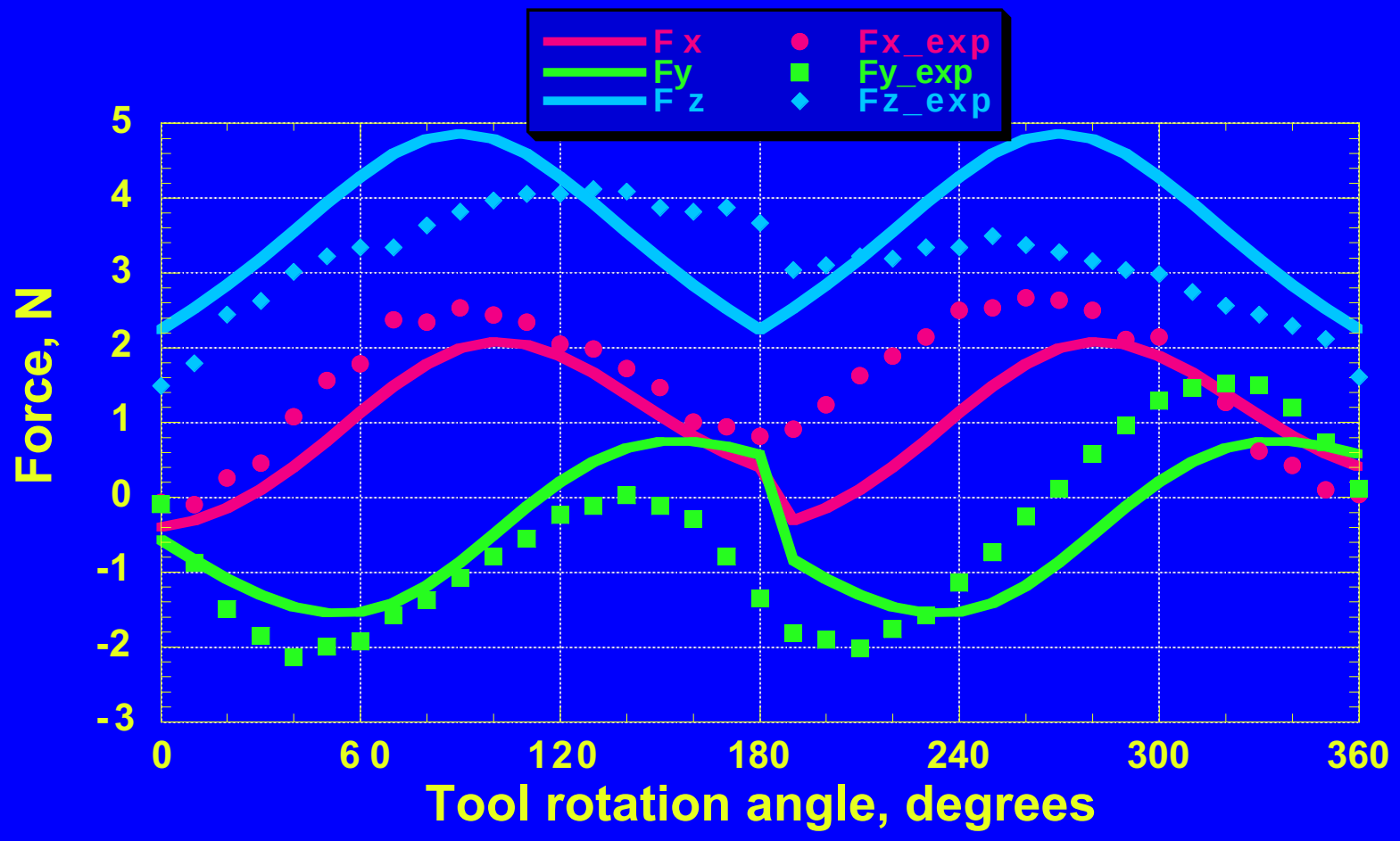

TOOL FORCES

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

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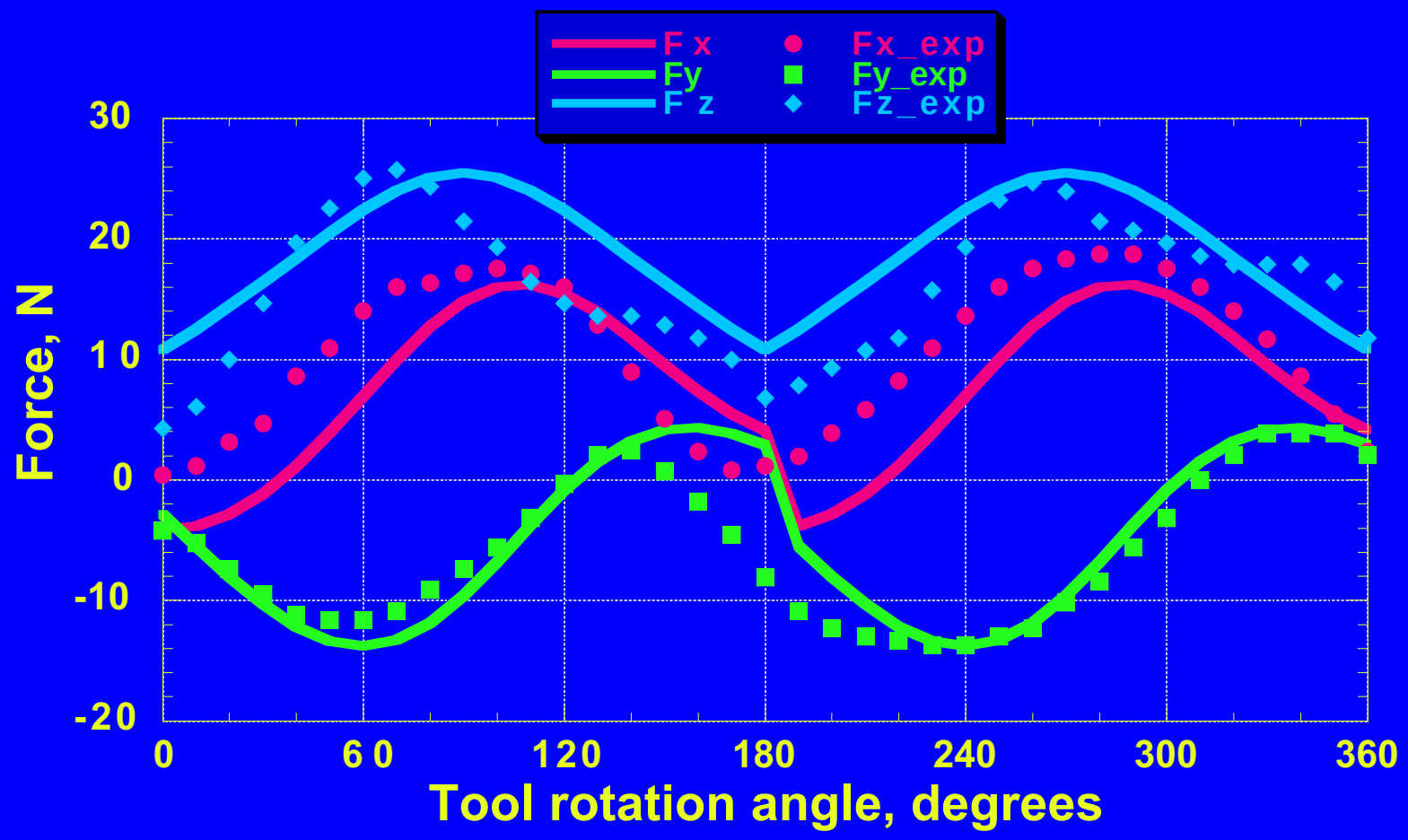

TOOL DEFLECTION

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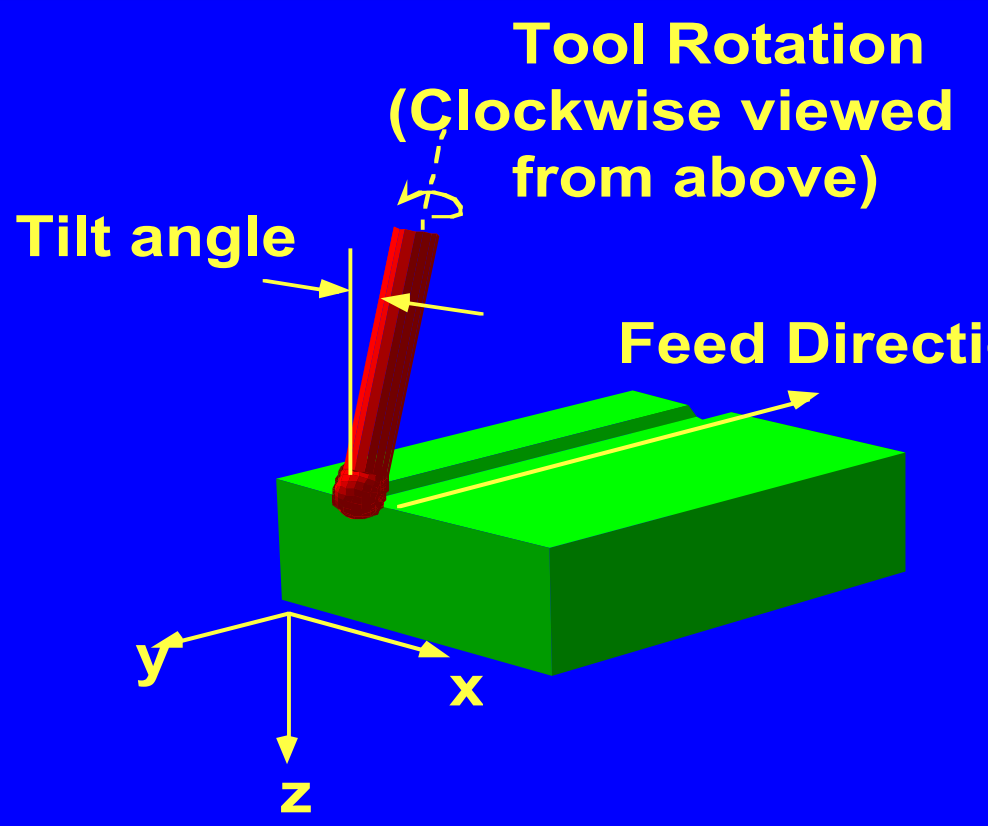
- **TOOL DEFLECTION EXPERIMENTS**
  - Slot with increasing depth
  - Thrust force reduces depth of cut
  - Stiffness depends on tilt of tool



50 deg tilt (no compensation)

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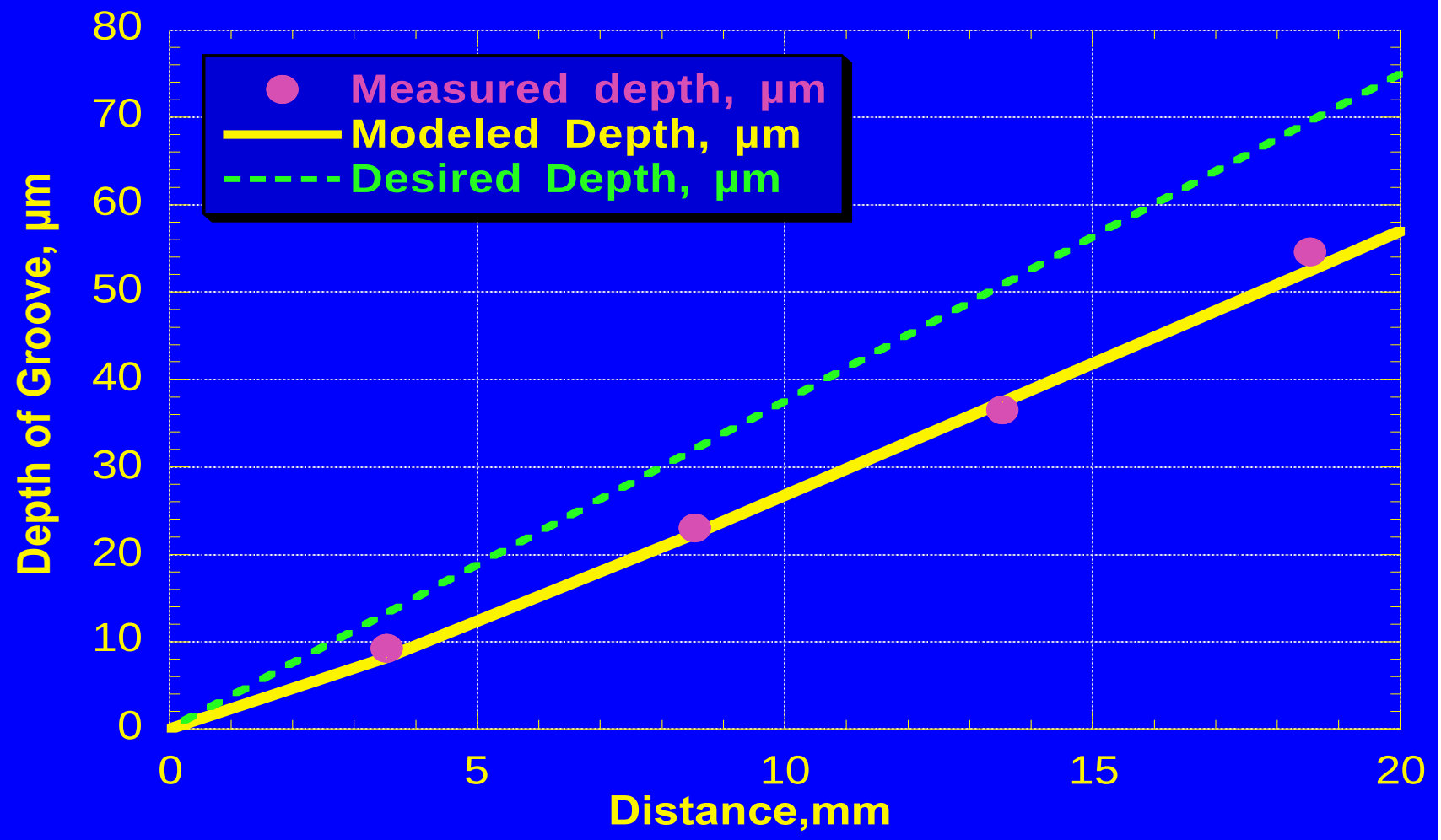

50 deg tilt (compensation)

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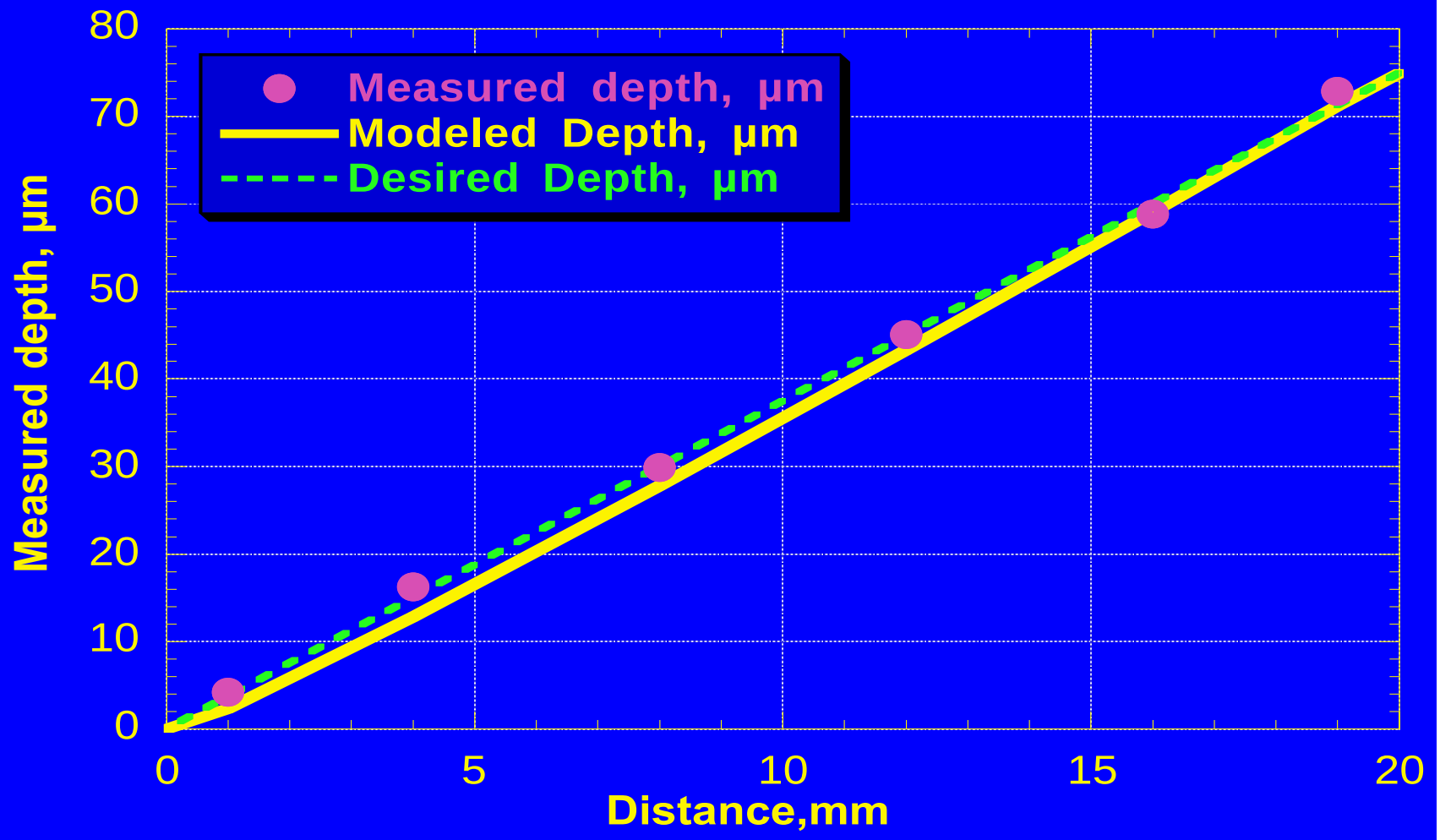

COMPENSATION EXPERIMENT

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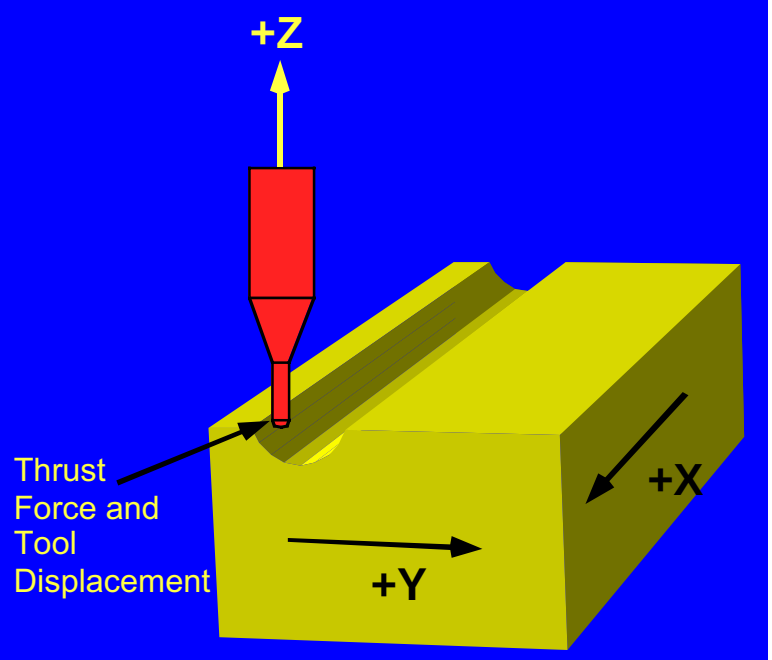
- Cut 0.5 mm deep groove with 1.5 mm radius ball end mill
- Remove 0.1 mm using 0.4 mm radius ball mill (sweep angle ± 50 deg)
- Compensate for tool deflection in y-z plane



TOOL FORCE DIRECTIONS

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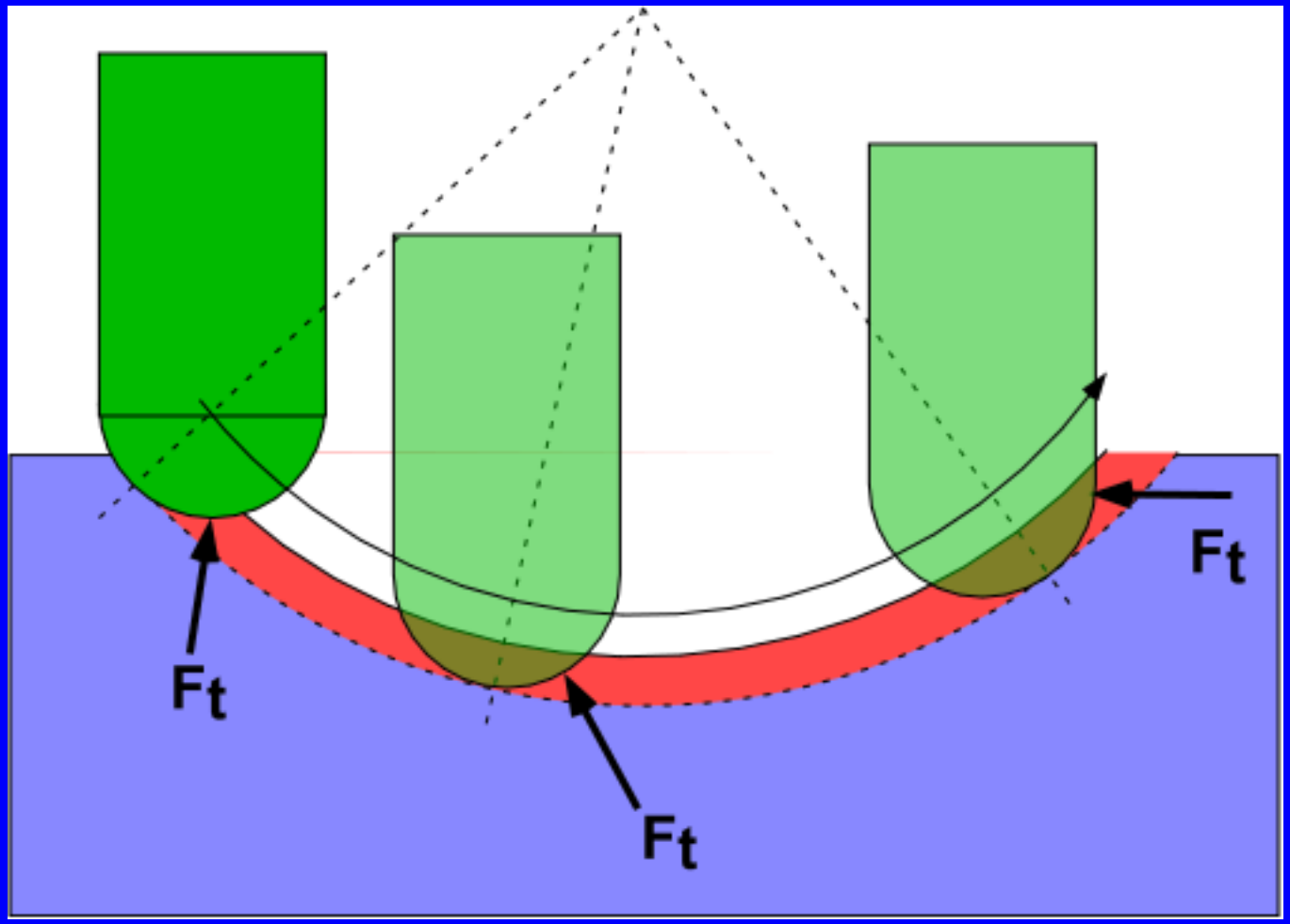

Groove with Short Tool

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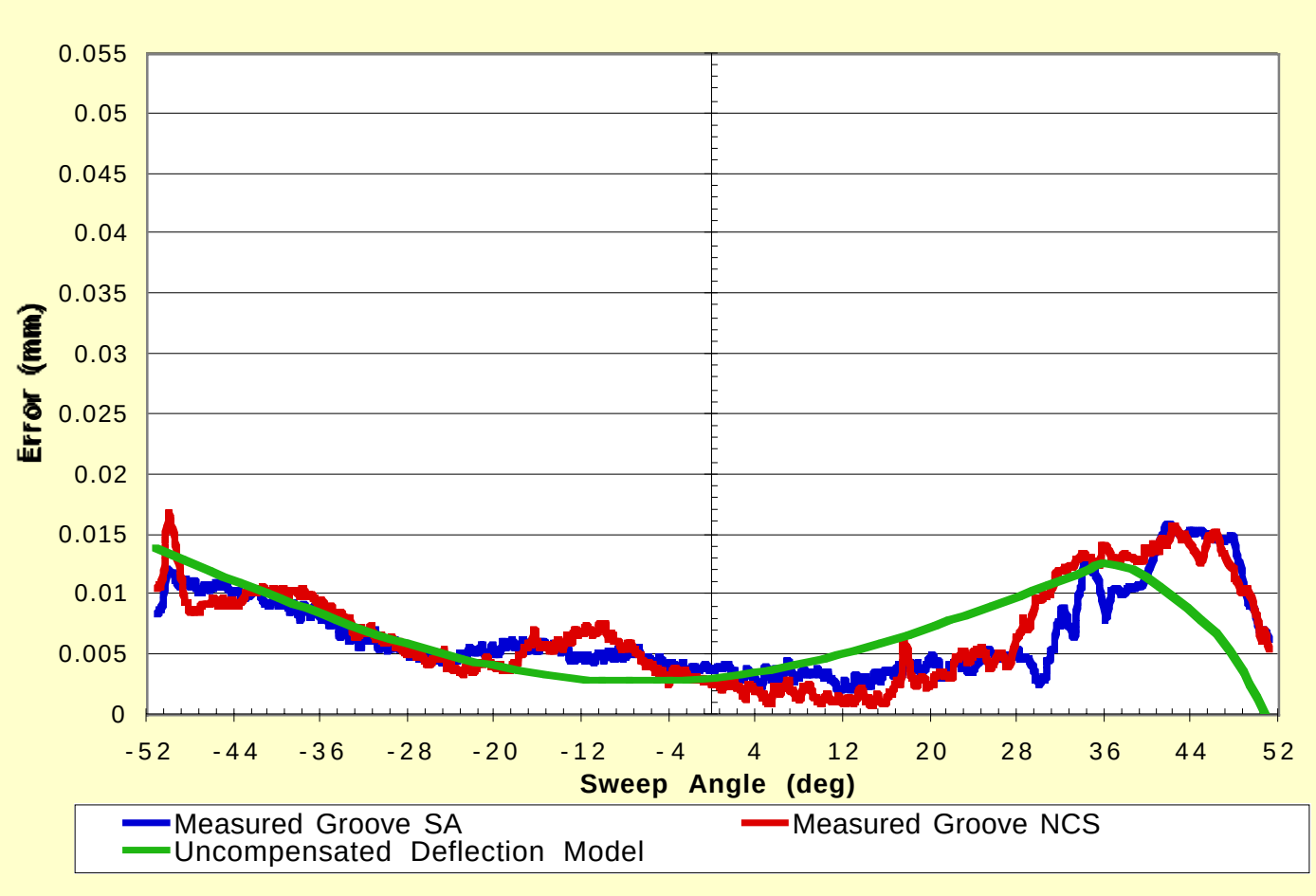

Groove with Long Tool

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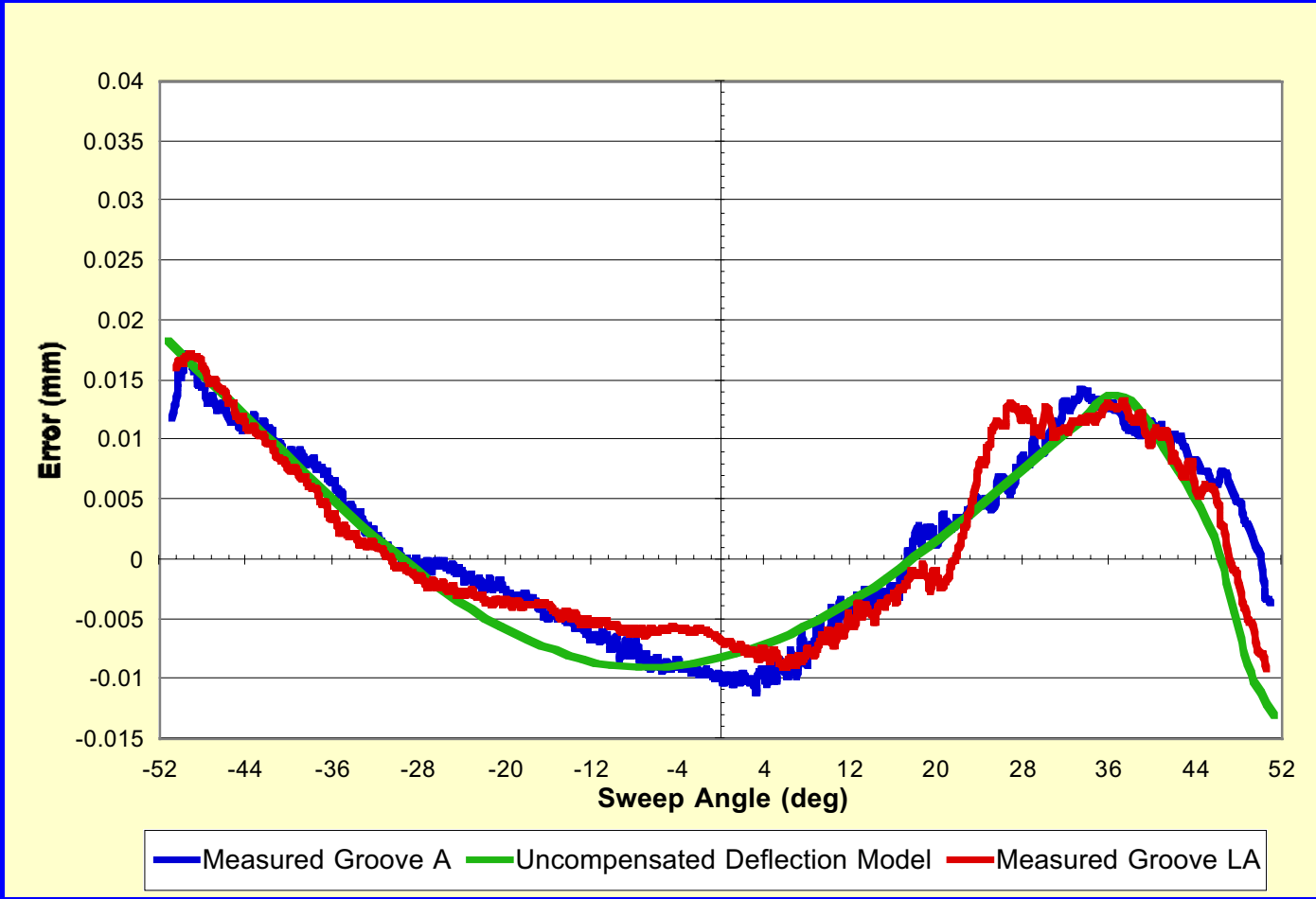

Groove - Extra Long Tool

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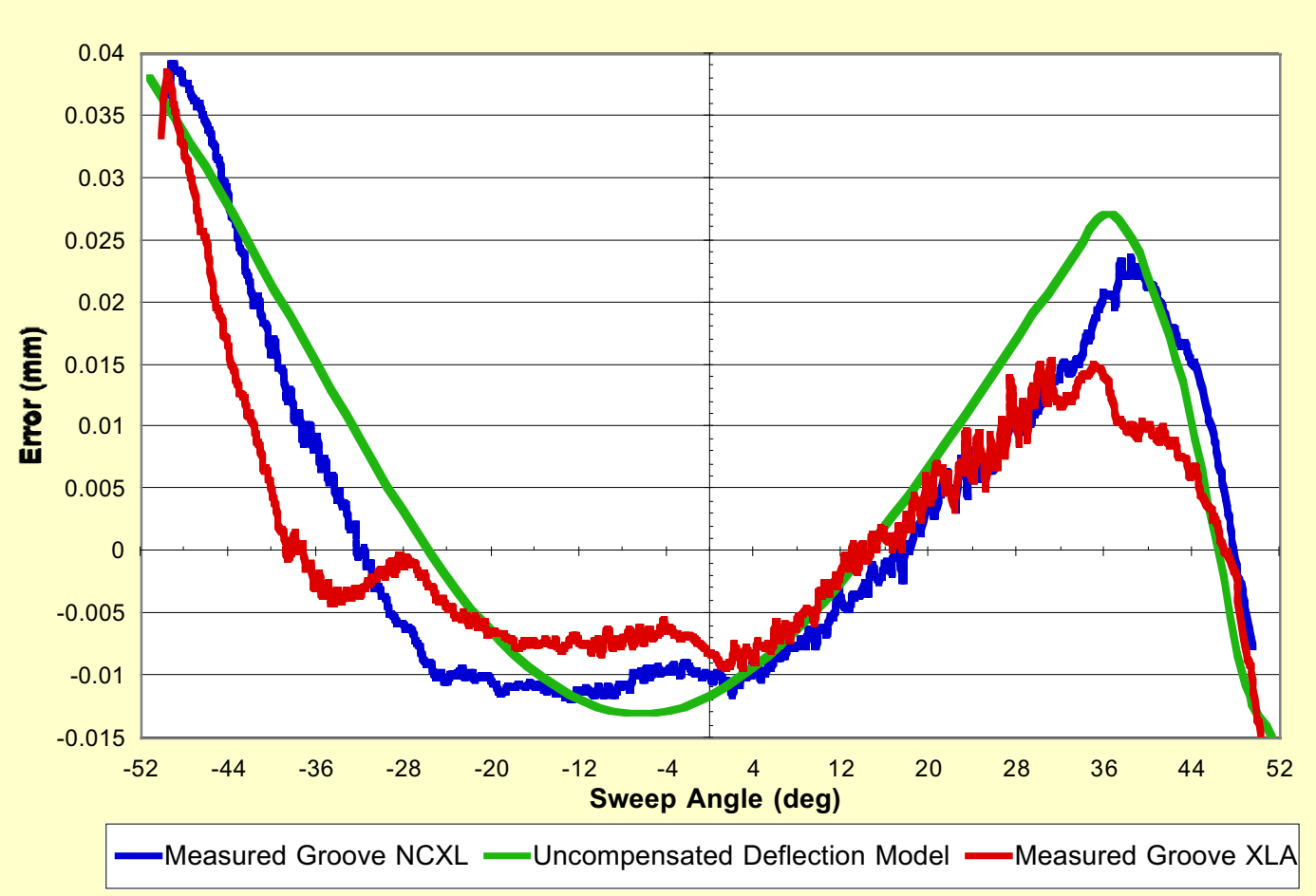

Compensated Groove Extra Long Tool

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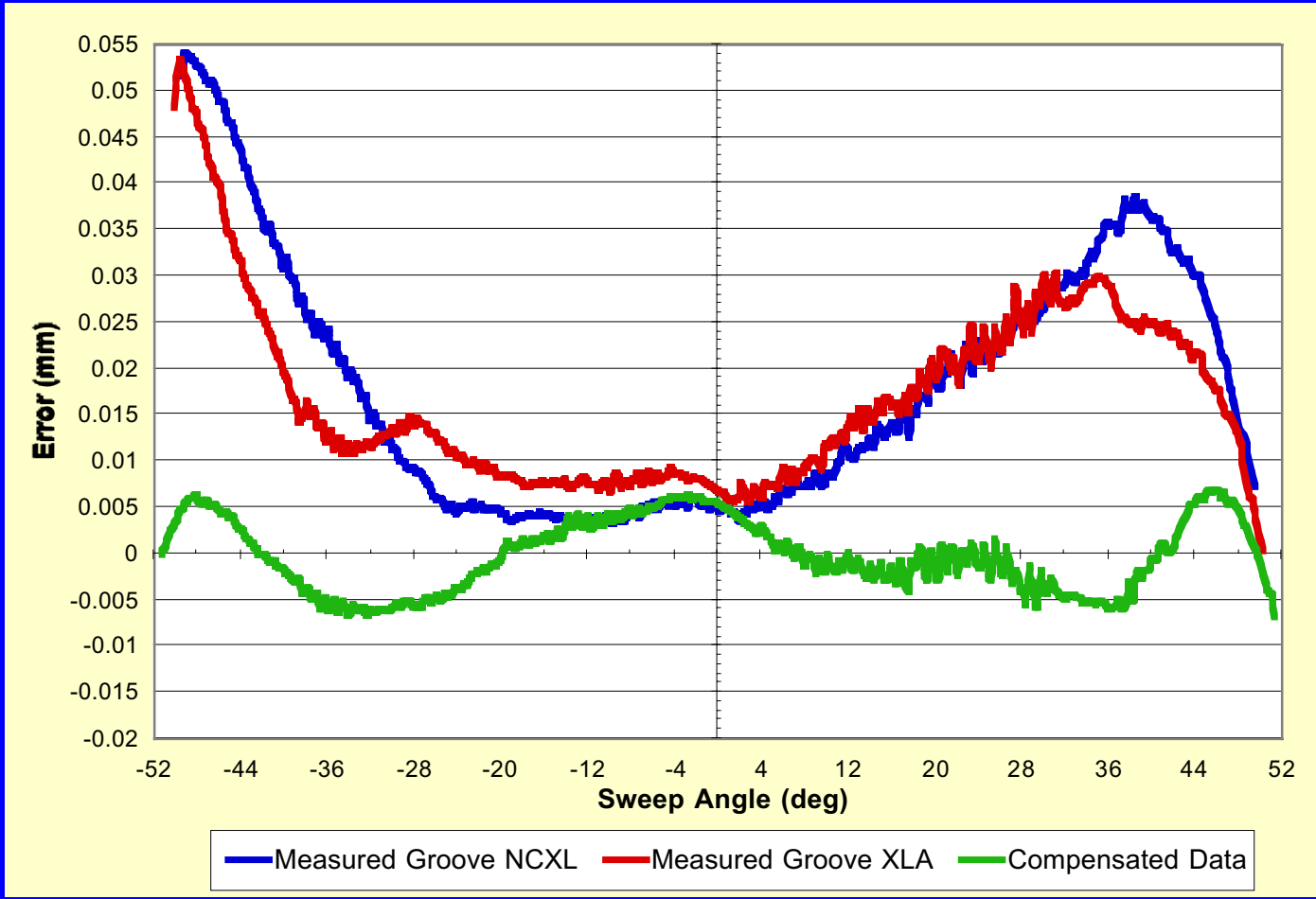

Best Fit Radii (1.6 mm)

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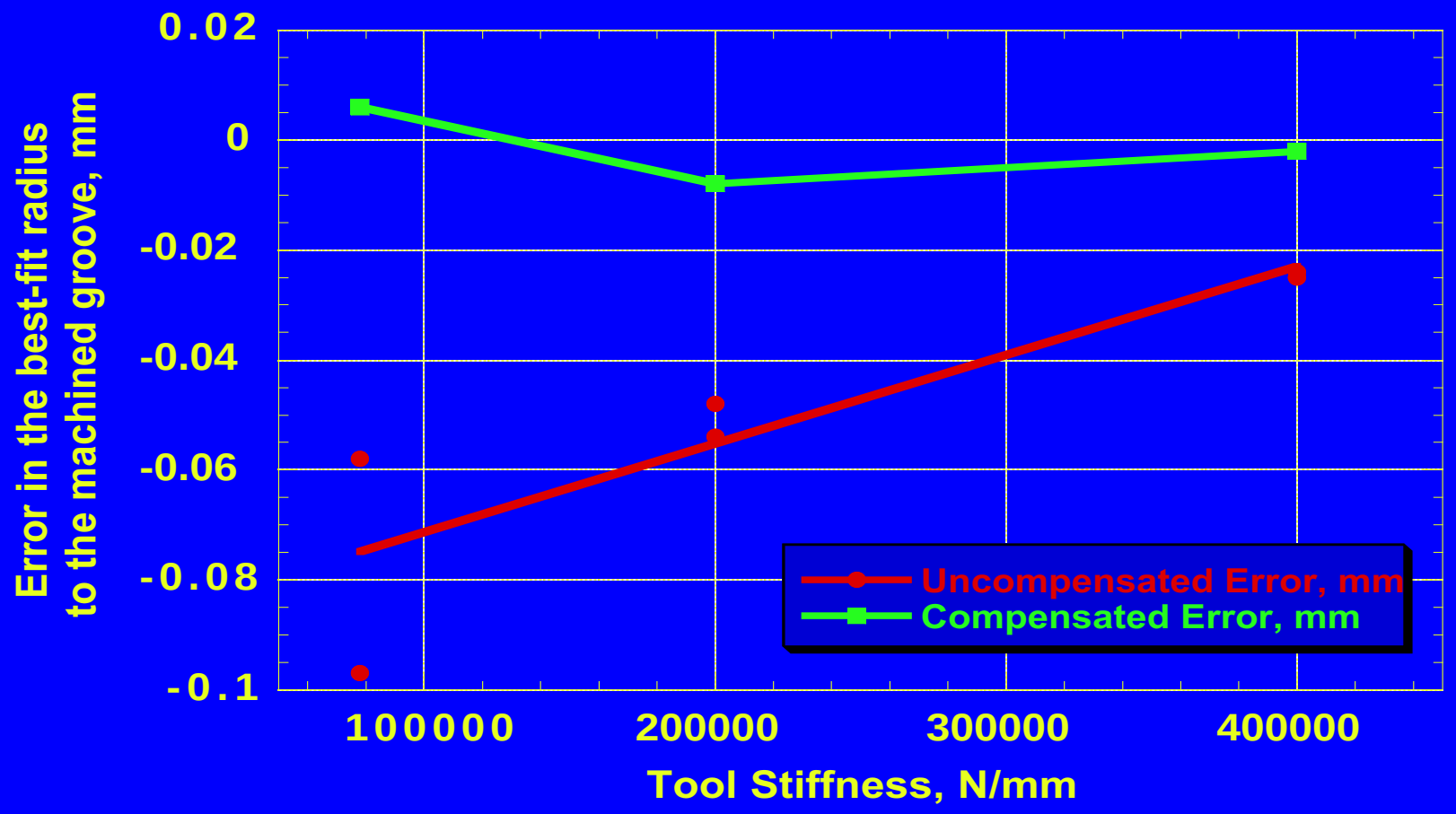

CONCLUSIONS

- 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