A Mechanistic Model of Cutting Force in the Micro End Milling Process

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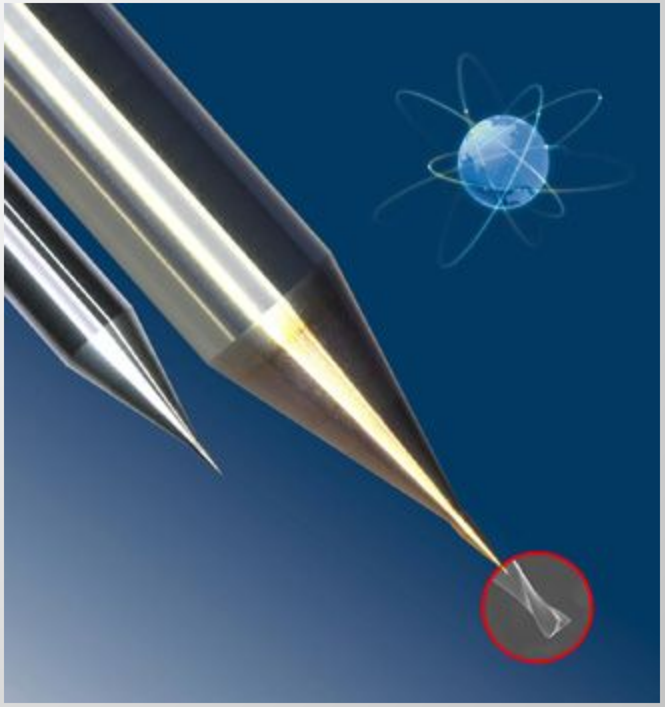
10/10/2007

Introduction:

- What is micro end milling? 1mm - .04μm dia
- Applications of micro end milling
- Micro end milling vs. Conventional end milling
  - Feed/tooth to tool radius
  - Cutting conditions
  - Detection of tool wear
- Various cutting force analyses



- Previous analyses
  - Analytic cutting force of the conventional end mill as a function of chip thickness and cutting area, Tlusty et al
  - Analytic cutting force model of micro end mill based on Tlusty , Bao et al
- Major shortcomings
  - Based mainly on differences between tool tip trajectories
  - Ignored the effect of tool edge radius

Operator’s tool life

Tool life is measured by:

- Visual inspection of tool edge
- Tool breaks
- Fingernail test
- Changes in cutting sounds
- Chips become ribbony, stringy
- Surface finish degrades
- Computer interface says
    - power consumption up
    - cumulative cutting time reaches certain level
    - cumulative number of pieces cut reaches certain value

Models & Design Principles

- Model based on the tool edge radius

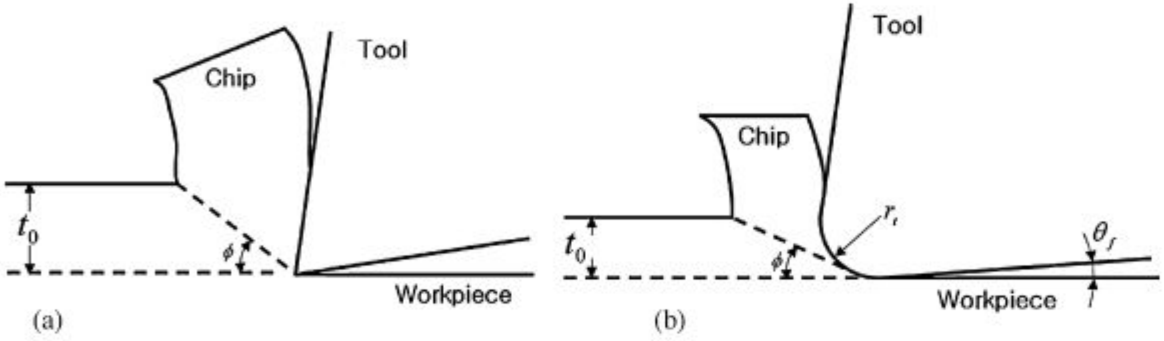


Fig. 1. Difference of conventional macro (a) and micro cutting (b).

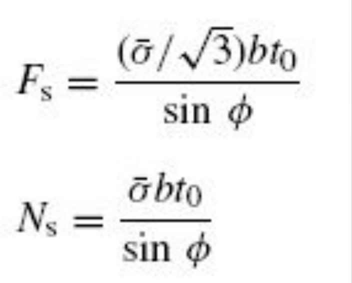
- When depth of cut is close or smaller than the tool edge radius, the radius effects cannot be ignored

Tool edge radius affects cutting mechanisms

- Elastic recovery in the flank face of the work piece
- Sliding due to the contact between the tool and the work piece
- Ploughing due to the tool edge

These cutting mechanisms change the cutter forces in the feed and normal directions

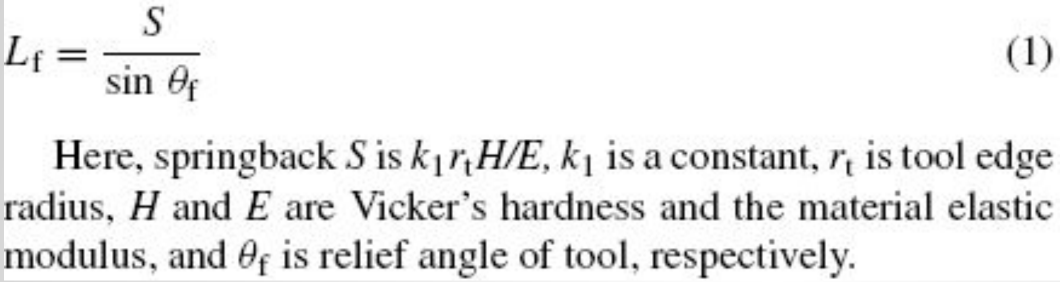
- Feed and normal forces plane shear and flank face contact friction



$$F_s = \frac{(\bar{\sigma}/\sqrt{3})bt_0}{\sin\phi}$$

$$N_s = \frac{\bar{\sigma}bt_0}{\sin\phi}$$

- Contact length of the tool on the work piece

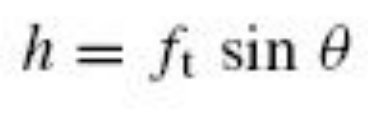


$$L_f = \frac{S}{\sin\theta_f} \qquad (1)$$

Here, springback S is $k_1 r_t H/E$, k_1 is a constant, r_t is tool edge radius, H and E are Vicker's hardness and the material elastic modulus, and θ_f is relief angle of tool, respectively.

- Chip thickness variation as a function of tool rotation angle θ

  f_t = Feed/tooth



$$h = f_t \sin\theta$$

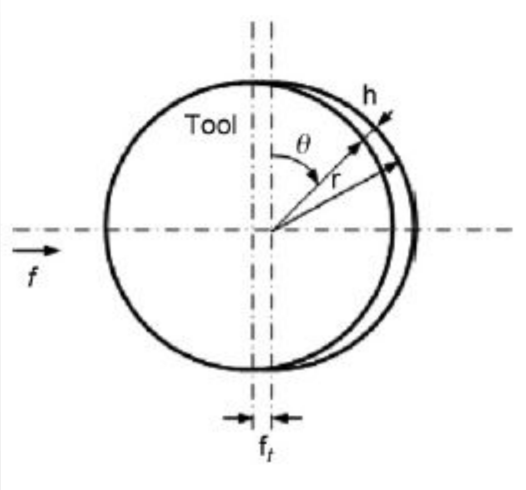


Fig. 2. End milling process.

- Principal cutting force and thrust cutting force

$$F_{\mathrm{c}} = F_{\mathrm{s}} \cos\phi + N_{\mathrm{s}} \sin\phi + F_{\mathrm{fc}}$$

$$F_{\mathrm{t}} = -F_{\mathrm{s}} \sin\phi + N_{\mathrm{s}} \cos\phi + F_{\mathrm{ft}}$$

- Final derivation of feed and normal cutting forces

$$\begin{aligned} F_x = [&C_1(\sin^2\theta_{\mathrm{e}} - \sin^2\theta_{\mathrm{s}}) + C_2(\sin 2\theta_{\mathrm{e}} - \sin 2\theta_{\mathrm{s}}) \\ &- C_4(\sin\theta_{\mathrm{e}} - \sin\theta_{\mathrm{s}}) + C_5(\cos\theta_{\mathrm{e}} - \cos\theta_{\mathrm{s}}) \\ &+ C_3(\theta_{\mathrm{e}} - \theta_{\mathrm{s}}) \\ F_y = [&C_3(\sin^2\theta_{\mathrm{e}} - \sin^2\theta_{\mathrm{s}}) + 0.5C_1(\sin 2\theta_{\mathrm{e}} - \sin 2\theta_{\mathrm{s}}) \\ &- C_5(\sin\theta_{\mathrm{e}} - \sin\theta_{\mathrm{s}}) - C_4(\cos\theta_{\mathrm{e}} - \cos\theta_{\mathrm{s}}) \\ &- C_1(\theta_{\mathrm{e}} - \theta_{\mathrm{s}})] \end{aligned}$$

$$\begin{aligned} C_1 &= -\frac{\bar{\sigma}\, f_{\mathrm{t}} r \cos\phi}{2\sqrt{3}\sin\phi\tan\beta} - \frac{\bar{\sigma}\, f_{\mathrm{t}} r}{2\tan\beta}, \\ C_2 &= -\frac{\bar{\sigma}\, f_{\mathrm{t}} r}{4\sqrt{3}\tan\beta} + \frac{\bar{\sigma}\, f_{\mathrm{t}} r \cos\phi}{4\sin\phi\tan\beta}, \\ C_3 &= \frac{\bar{\sigma}\, f_{\mathrm{t}} r}{2\sqrt{3}\tan\beta} - \frac{\bar{\sigma}\, f_{\mathrm{t}} r \cos\phi}{2\sin\phi\tan\beta}, \\ C_4 &= \frac{Y L_{\mathrm{f}} r}{\sqrt{3}\tan\beta}, \quad C_5 = \sqrt{3}C_4 \end{aligned}$$

Experiment

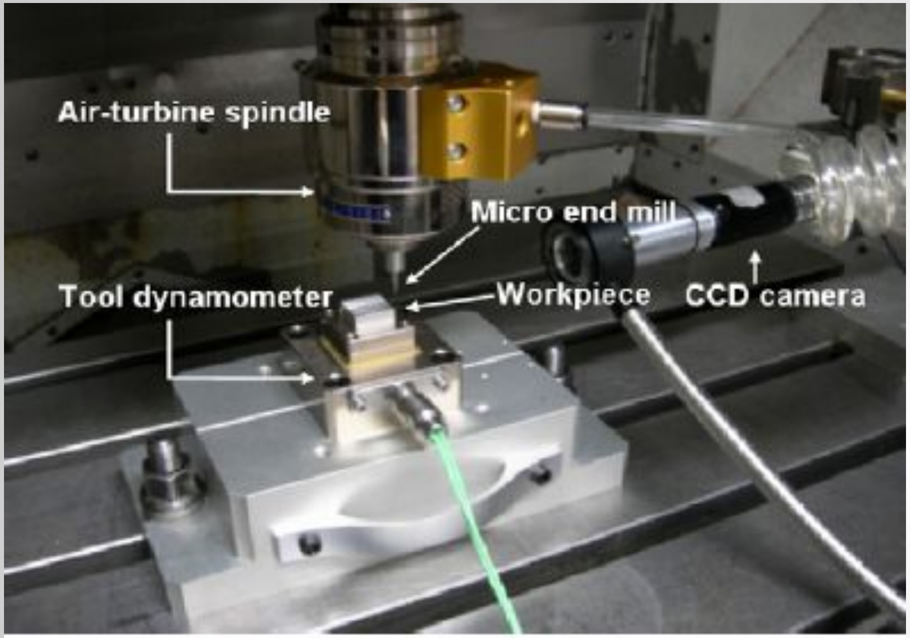


Fig. 4. Experimental set-up.

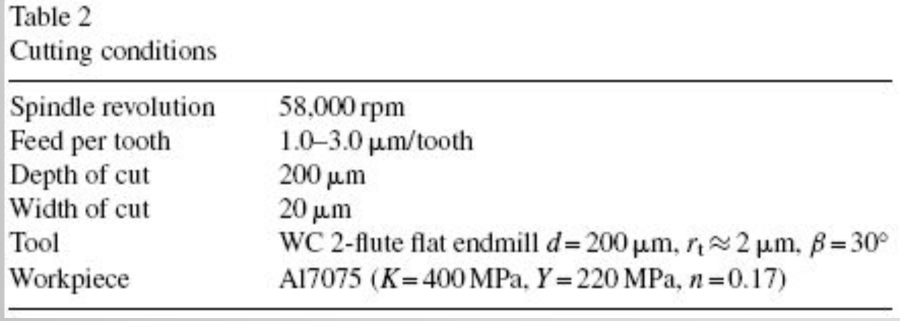


Table 2
Cutting conditions

Spindle revolution	58,000 rpm
Feed per tooth	1.0–3.0 μm/tooth
Depth of cut	200 μm
Width of cut	20 μm
Tool	WC 2-flute flat endmill $d = 200\ \mu\text{m}$, $r_t \approx 2\ \mu\text{m}$, $\beta = 30°$
Workpiece	Al7075 ($K = 400$ MPa, $Y = 220$ MPa, $n = 0.17$)

Results

- Previous experiments & models
  - Conventional cutting
    - Normal Force > Feed Force
  - Micro cutting according to Bao and Tansel
    - Normal Force > Feed Force

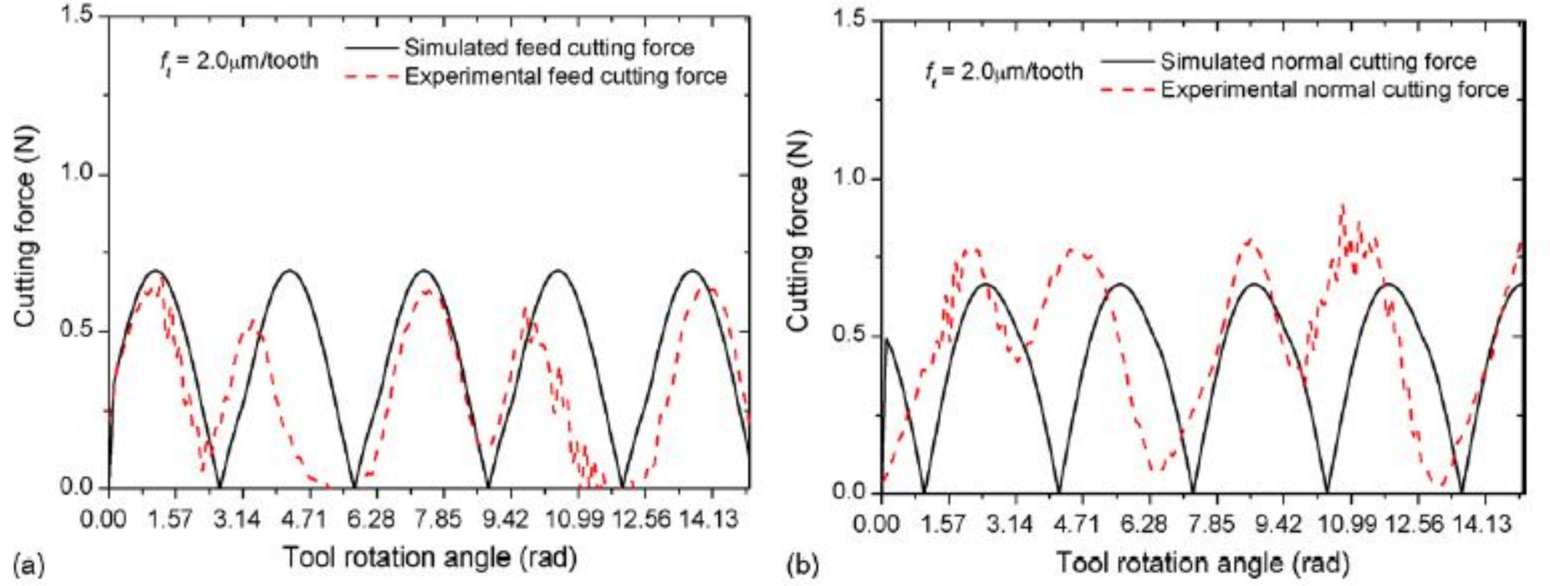


Fig. 6. Comparison of simulated and experimental cutting force for feed per tooth 2.0 μm. (a) Feed cutting force; (b) normal cutting force.

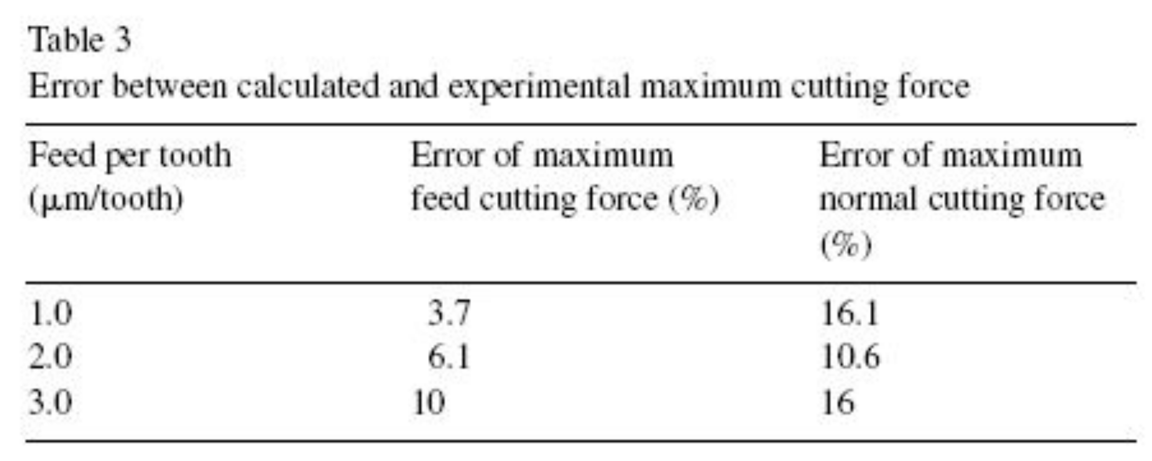


Table 3
Error between calculated and experimental maximum cutting force

Feed per tooth (μm/tooth)	Error of maximum feed cutting force (%)	Error of maximum normal cutting force (%)
1.0	3.7	16.1
2.0	6.1	10.6
3.0	10	16

- Percent error was relatively low
- Percent error from existing models and experiments not cited for comparison

Conclusions

- Derived a model that predicted micro end milling cutting forces
- Included the tool edge radius effect
- Predicted feed and normal cutting forces due to the tool edge radius

Why is it important?

- Help predict tool wear and failure
- Extend tool life through known cutting conditions

Industries affected

- Electronics, biomedical, aerospace, etc
- High precision and accurate dimension cutting