INVESTIGATING SIZE EFFECT IN ORTHOGONAL MICRO CUTTING OF CP TITANIUM

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Alp AKSIN, Dr. Yiğit KARPAT

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BILKENT UNIVERSITY
MECHANICAL ENGINEERING DEPARTMENT
Micro System Design and Manufacturing Lab.
me.bilkent.edu.tr

contact: alp.aksin@bilkent.edu.tr
alp.aksin@roketsan.com.tr

Contents

Introduction

Micromachining is used in micro mechanical component, micro mold production, medical transplants, MEMS etc.

Commercially pure titanium has applications in many industry.

Size affect is well known physical phenomenon in microscale cutting conditions.

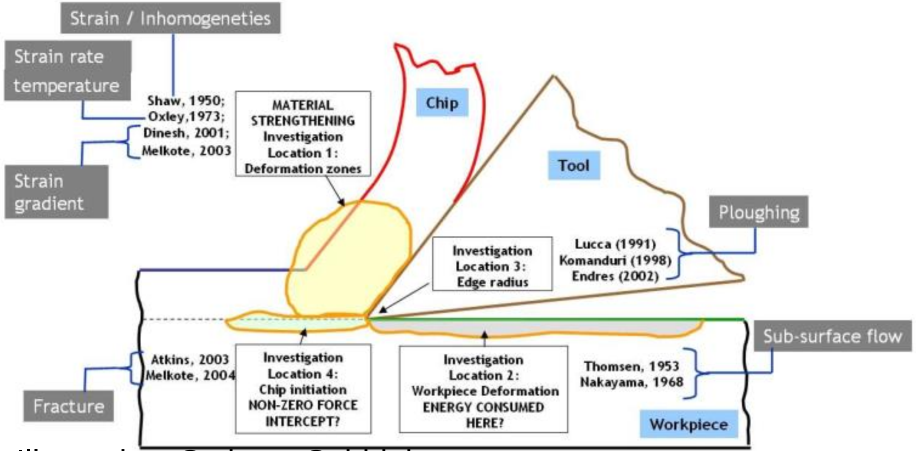
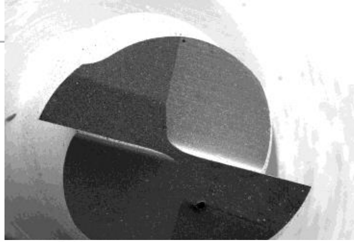
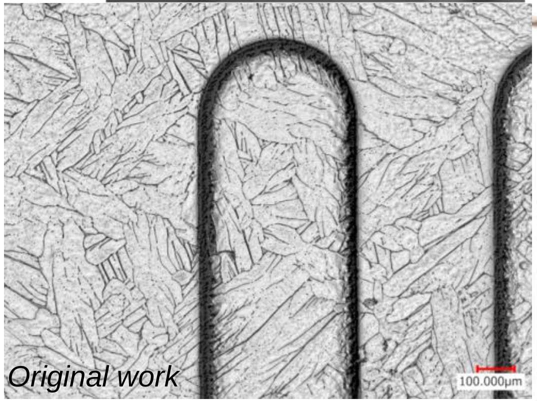
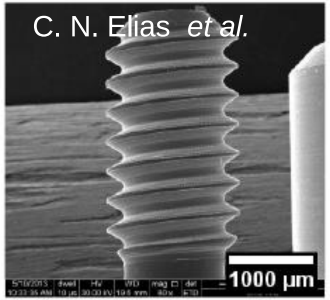


Illustration: Sathyan Subbiah

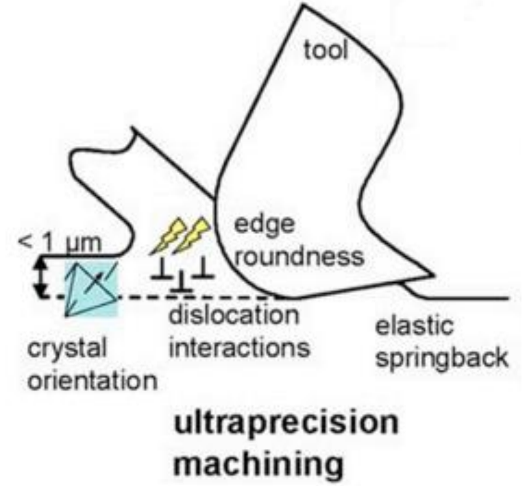






Introduction

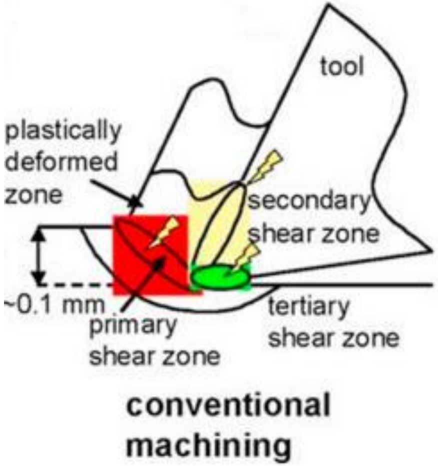
Micro cutting



**RTS<1*

- *Negative rake angle occurs and material compressed while cutting*
- *Size effect become important*

Macro cutting



**RTS >1*

- *Material separated*

Shear by itself unable to explain size effect in micro machining conditions.

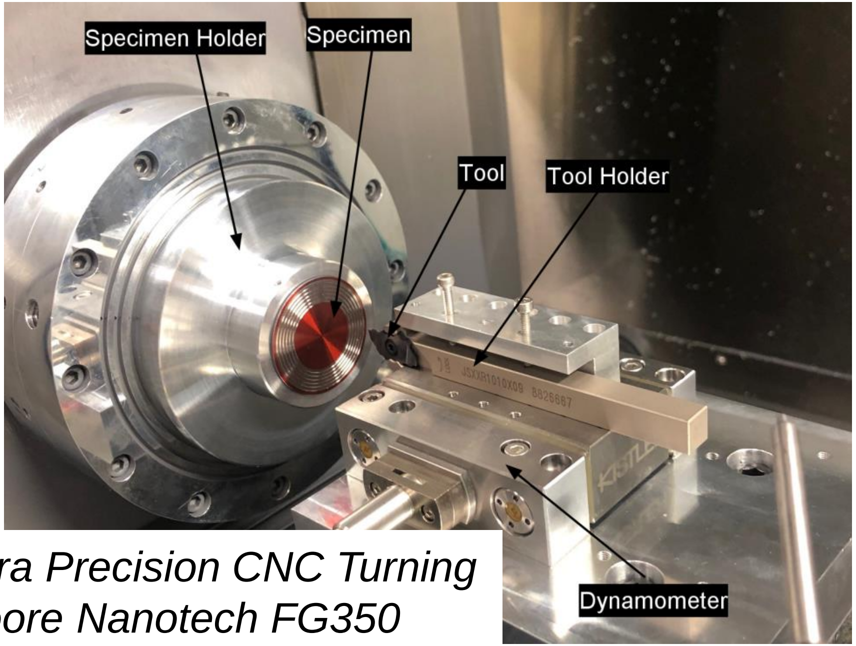
Ploughing, fracture and friction must be considered.

Tool edge radius and effective rake angle also have important role.

Illustration: M.A. Rahman et al.

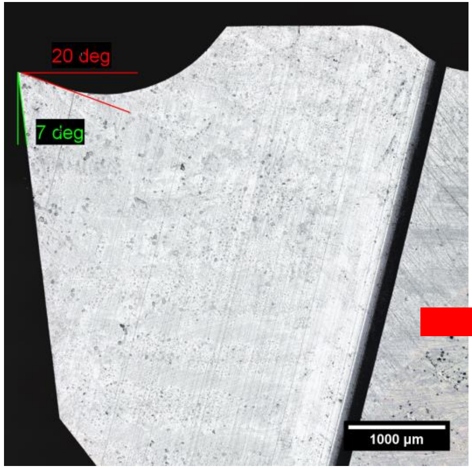
**: Relative tool sharpness (h/re)*

Orthogonal Cutting Tests

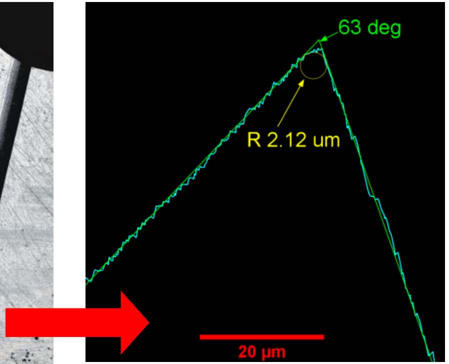


Ultra Precision CNC Turning
Moore Nanotech FG350

The Cutting tool used in tests:
In as-received condition r_e is 2μm



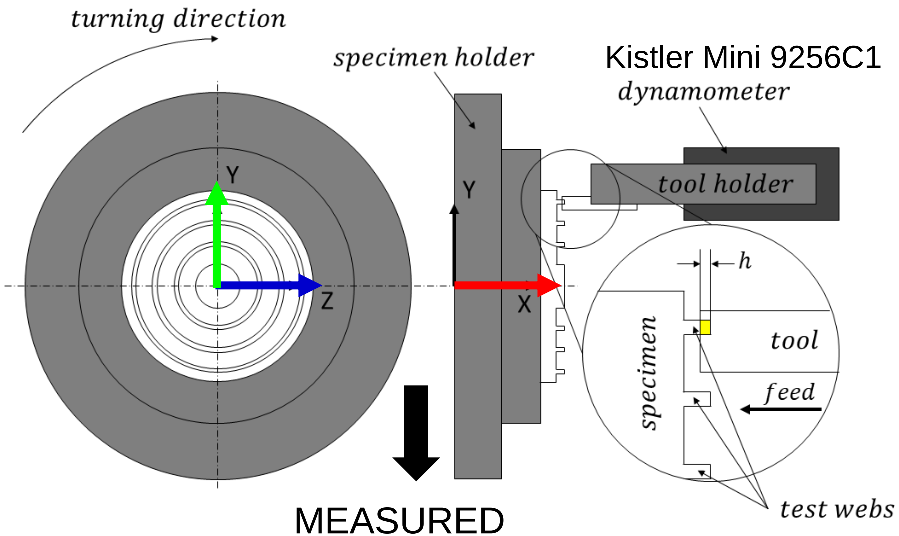
Cutting tool side view



LSM profile measurement

Orthogonal Cutting Tests

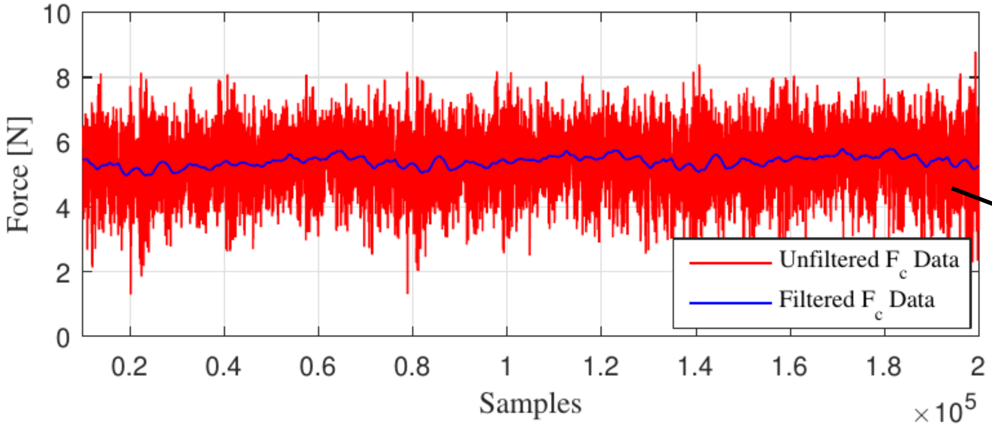
Parameters	Values
Material	CP Ti Grade 2 (As received)
Cutting Speed [m/min]	40
Uncut chip thickness [μm]	0.25, 0.5, 1, 2, 3, 4, 5, 6
Width of cut [μm]	280
Tool	Tungaloy JXPG06R10F SH725
Tool rake angle [°]	20
Tool clearance angle [°]	7
Tool edge radius [μm]	5
Tool width [μm]	980
Tool usage [−]	Up-sharp tool edge used per test



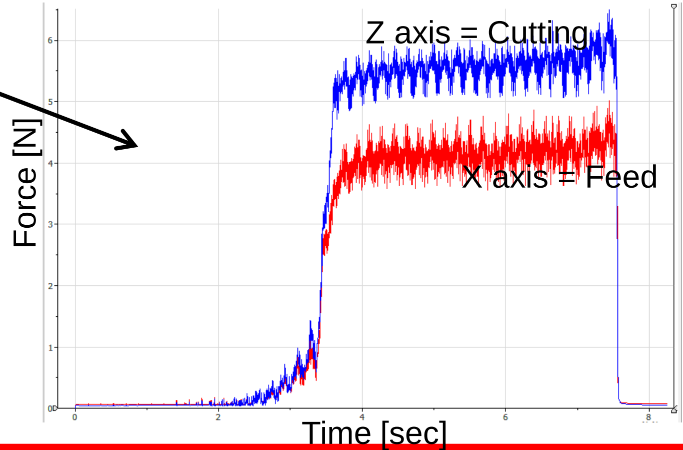
MEASURED
Cutting Force
Deformed Chip Thickness
Width of cut
Cutting Tool Edges

Orthogonal Cutting Tests

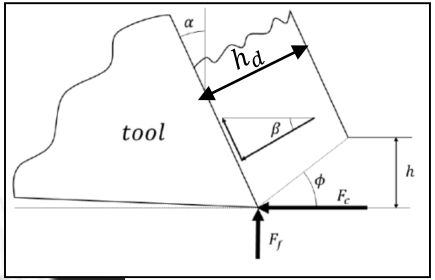
Force data filtered by using Butterworth Low Pass Filter



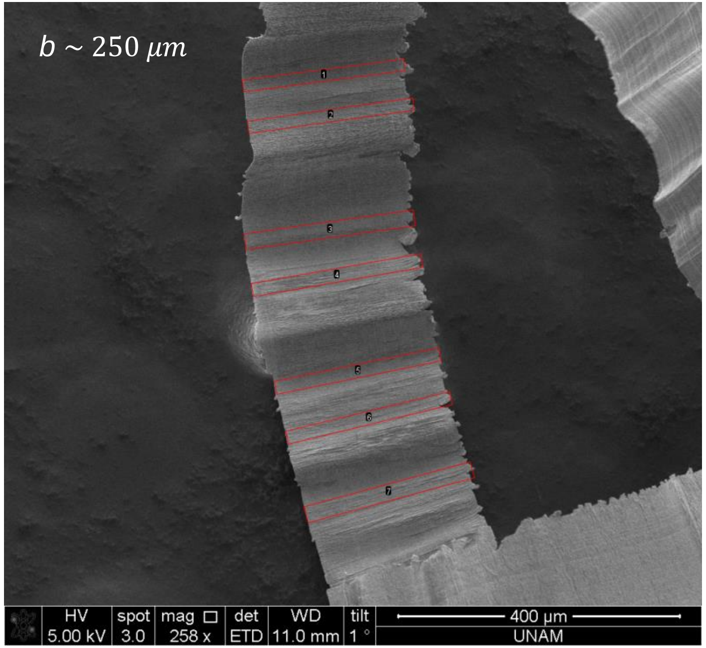
Spindle revolution frequency is used as the threshold for low pass filter.

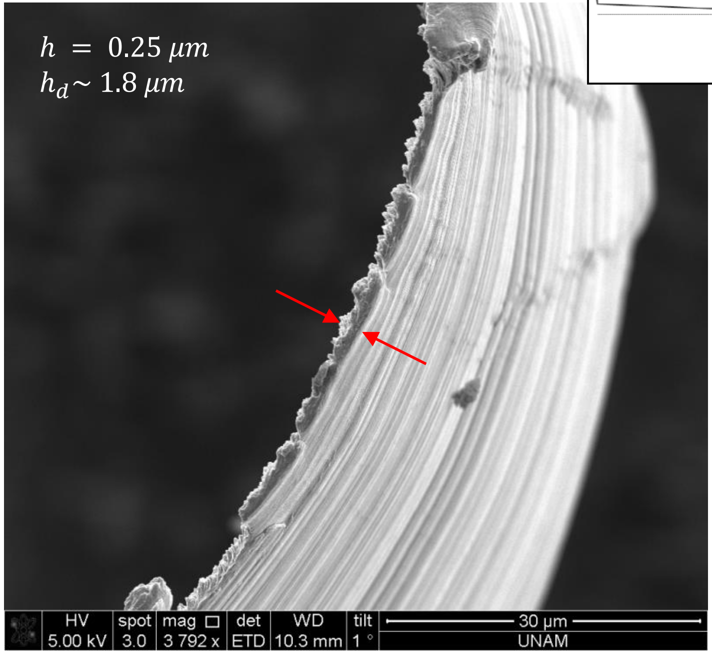


Orthogonal Cutting Tests

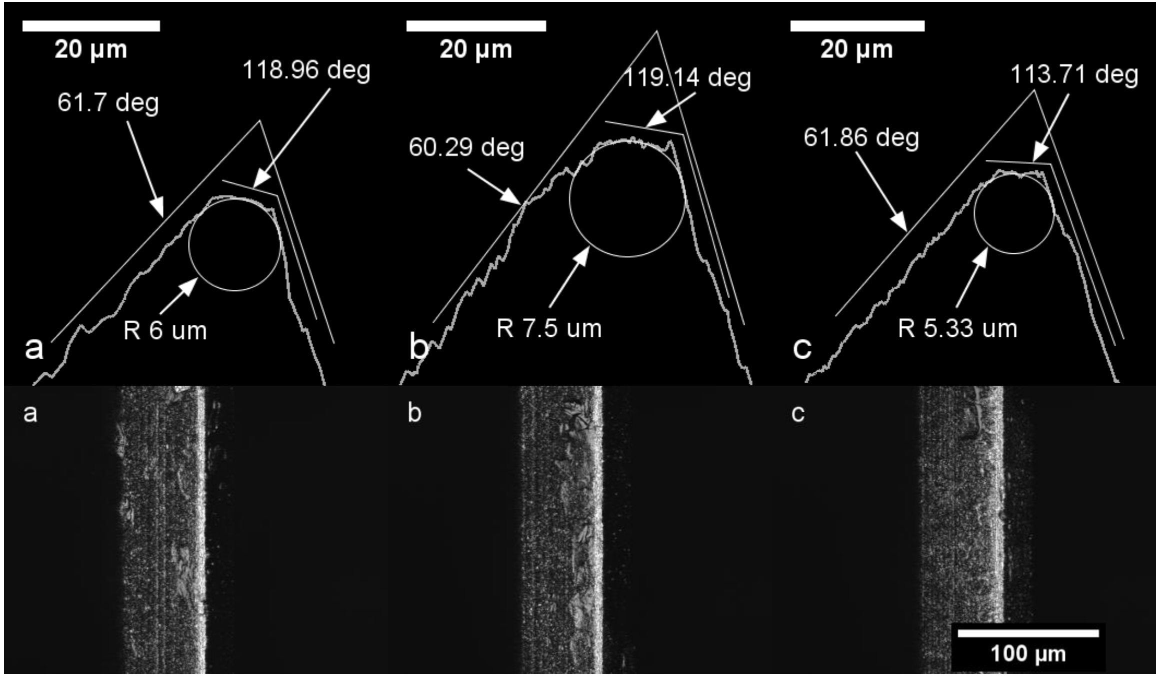


SEM measurements of chip width and thickness





Orthogonal Cutting Tests



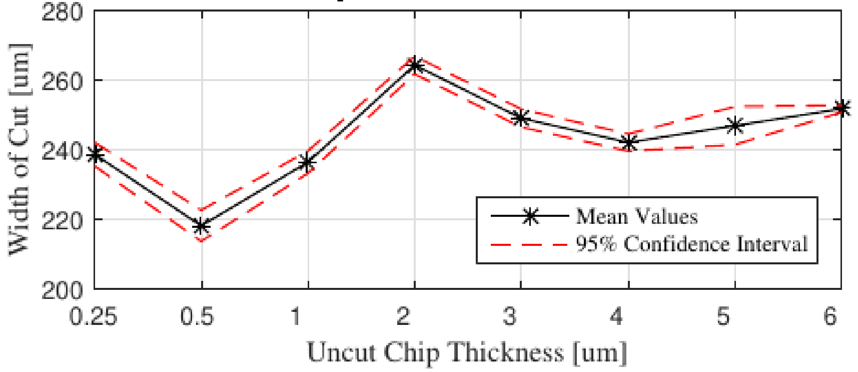
Tool measurement and images used in as-received specimen.

Tool profile measurements of cutting tool via Keyence LSM

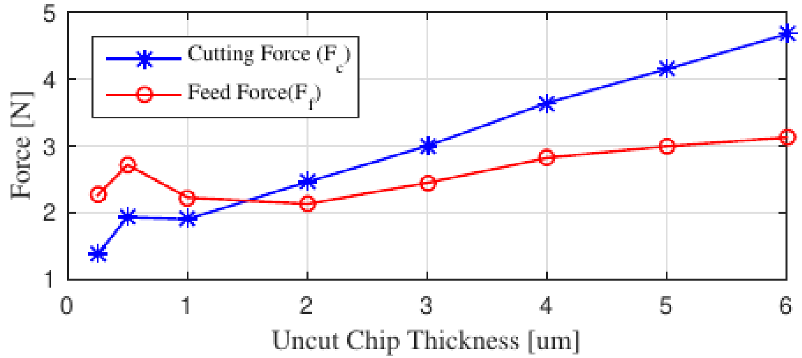
Orthogonal Cutting Tests

Normalization

Chip Widths

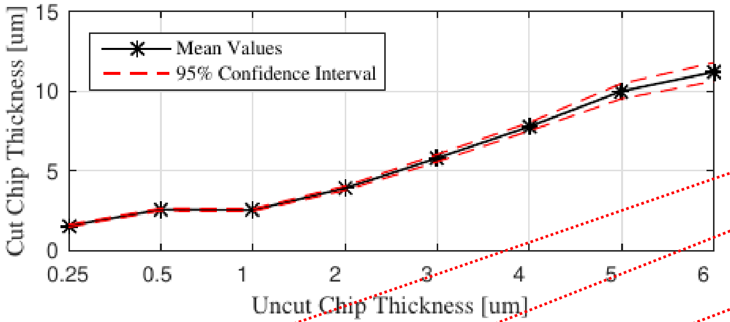


Force measurements

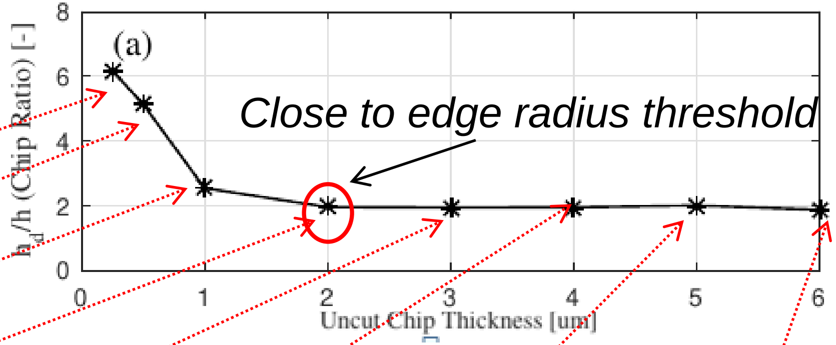


Orthogonal Cutting Tests

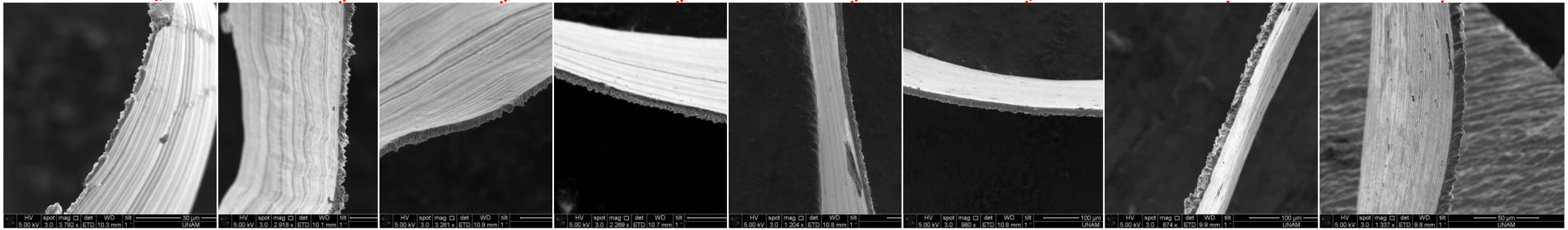
Cut chip thickness measurement results



Chip ratio

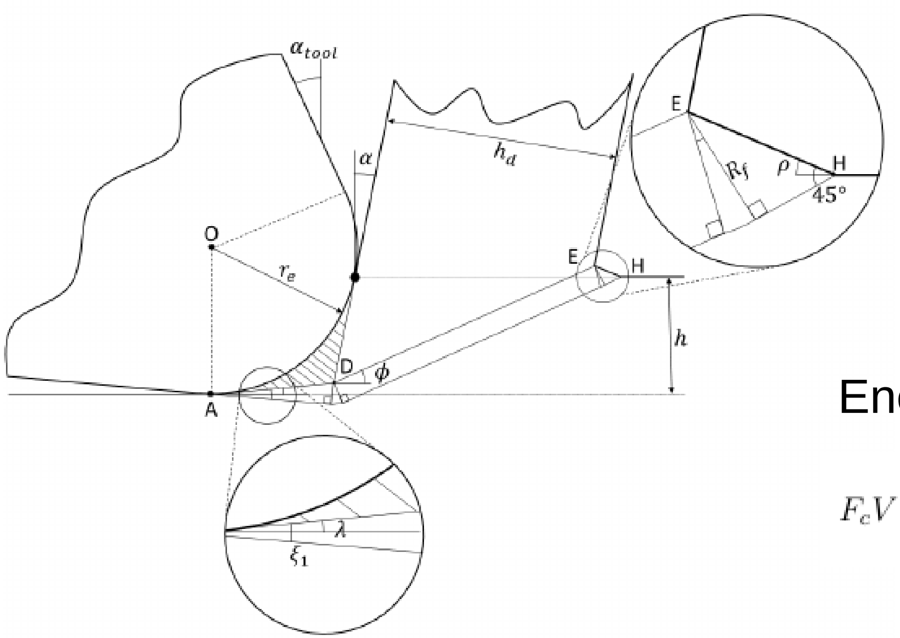


0.25 um | 0.5 um | 1 um | 2 um | 3 um | 4 um | 5 um | 6 um



Slip Line Field Model

The modified Atkins metal cutting model



- The model includes tool edge radius effect. [11]
- Assumes a dead metal zone (DMZ) in front of the tool edge
- Rake angle of the tool can actively change according to uncut chip thickness

Energy equation

$$F_c V = \frac{\tau_y h w \cos(\alpha) V}{\sin(\phi)\cos(\phi-\alpha)} + \frac{F_r \sin(\phi) V}{\cos(\phi-\alpha)} + \frac{F_p \sin(\xi_1-\lambda) V}{\xi_1} + R w V$$

shearing *friction* *fracture*

Slip Line Field Model

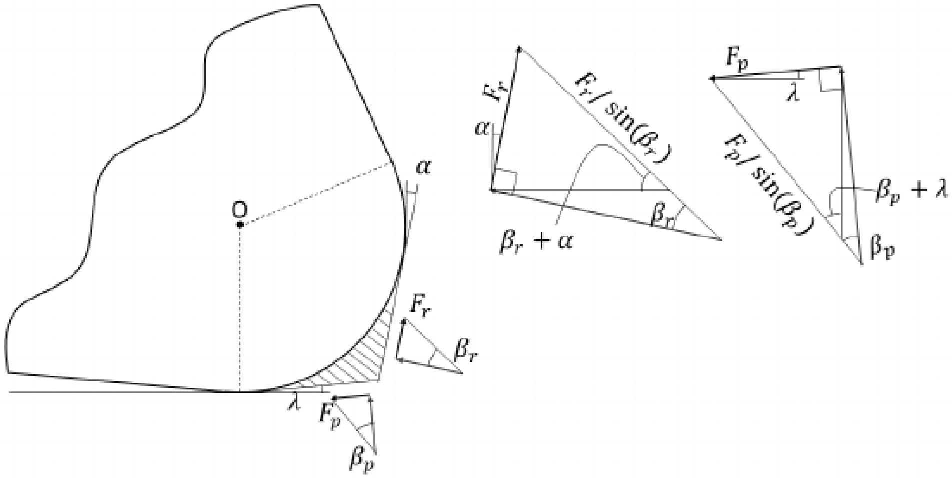
Minimum energy principle $dF/d\phi$

$$0 = \frac{\sin(\beta_r)}{\cos(\beta_r - \alpha)}\left[\gamma + \frac{mr_e(1+\sin(\alpha))}{h\cos(\lambda - \alpha)}N + Z\right] - \ldots$$

$$Q\left[\frac{\cos(2\phi - \alpha)}{\sin^2(\phi)} + \frac{mr_e(1+\sin(\alpha))\sin(\beta_p + \lambda)\sin(\beta_r)}{h\cos(\lambda - \alpha)\sin(\beta_p)\cos(\beta_r - \alpha)}\right]$$

$$Q = \left[1 - \frac{\sin(\phi)\sin(\beta_r)}{\cos(\phi - \alpha)\cos(\beta_r - \alpha)}\right]$$

$$N = \left[\frac{\sin(\xi_1 - \lambda)}{\xi_1} - \frac{\sin(\beta_r)\sin(\phi)\sin(\beta_p + \lambda)}{\cos(\phi - \alpha)\cos(\beta_r - \alpha)\sin(\beta_p)}\right]$$



The model considers two friction angle β_p, β_r, Depending on tool edge and DMZ.

Slip Line Field Model

Slope intercept

$$F_c = \frac{\tau_y h w \cos(\alpha)}{\sin(\phi)\cos(\phi-\alpha)Q} - \frac{m\tau_y |AD| w}{Q} N + \frac{Rw}{Q}$$

Solution strategy

$$N = \left[\frac{\sin(\xi_1 - \lambda)}{\xi_1} - \frac{\sin(\beta_r)\sin(\phi)\sin(\beta_p + \lambda)}{\cos(\phi-\alpha)\cos(\beta_r-\alpha)\sin(\beta_p)}\right]$$

Inclination angle
Friction factor

λ, m → β_p, ρ

Plowing angle
Prow angle

Accepted as known

Using slip line field angles

$$0 = h_d - \frac{h}{\sin(\phi)} sin(0.5\pi - \phi + \alpha)$$

Cutting force data

ϕ → β_r → τ_y, R

Using slip line field and circular edge assumption.

Minimum Energy Principle

r_e, α_{tool} → α

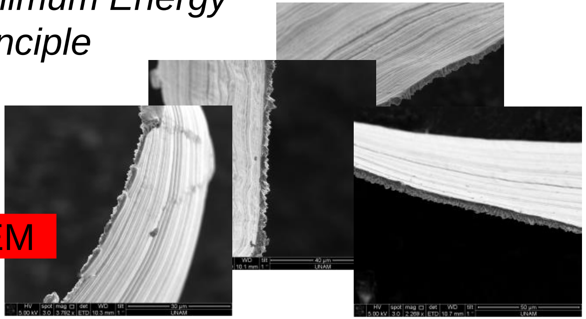
Edge radius
Tool rake angle

Effective rake angle

Using circular tool edge assumption

Cut Chip thickness Data

SEM

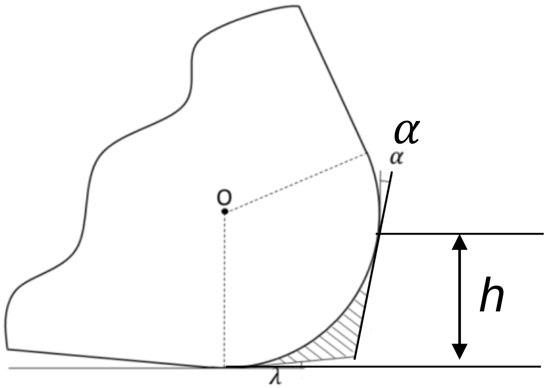


*Our method directly uses cut chip thickness data!

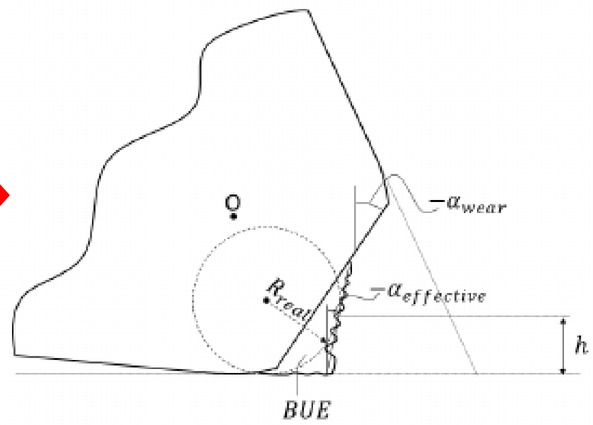
Slip Line Field Model

Round tool edge assumption may not be the case in micro-cutting conditions.

- The change in the rake angle may not be significant.
- Wear and BUE may change active rake angle during cutting.

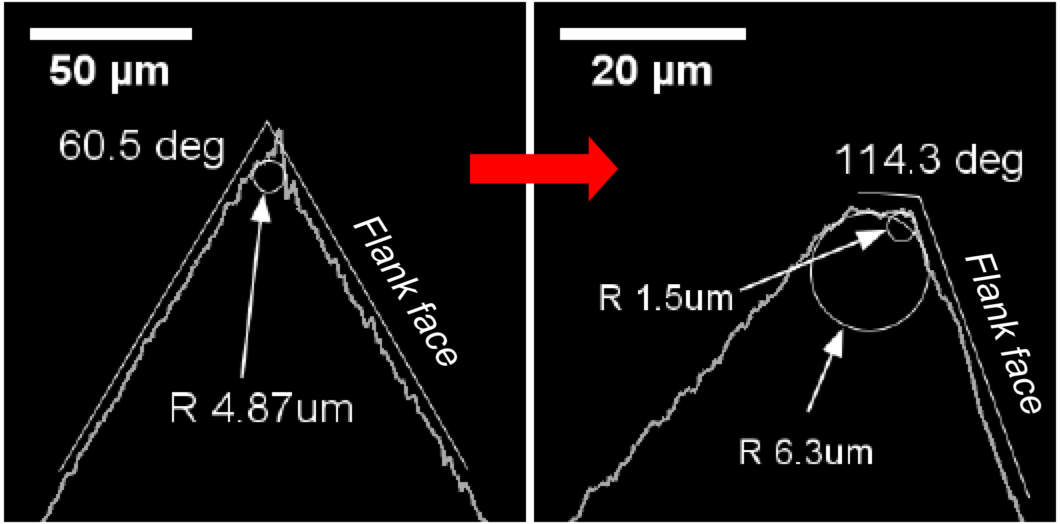


variable rake angle
(perfectly circular tool edge)



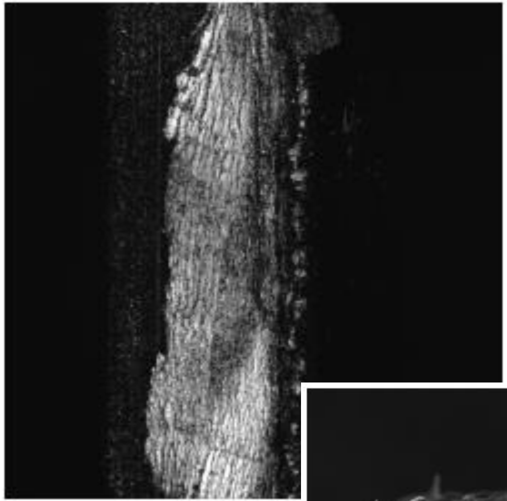
constant rake angle

Tool wear and build up edge (BUE) formations are observed on tool after cutting.

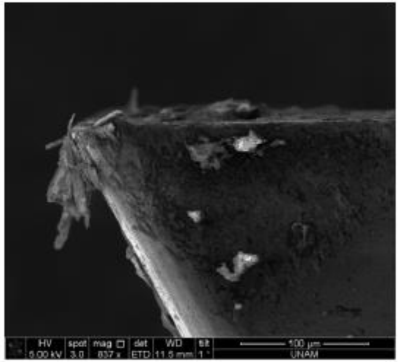


Before cutting *After cutting*

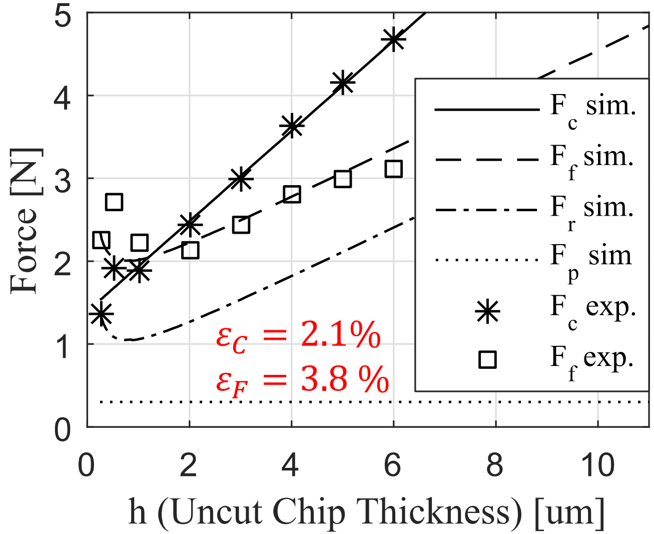
Rake angle actively changed during cutting!



BUE Evidence

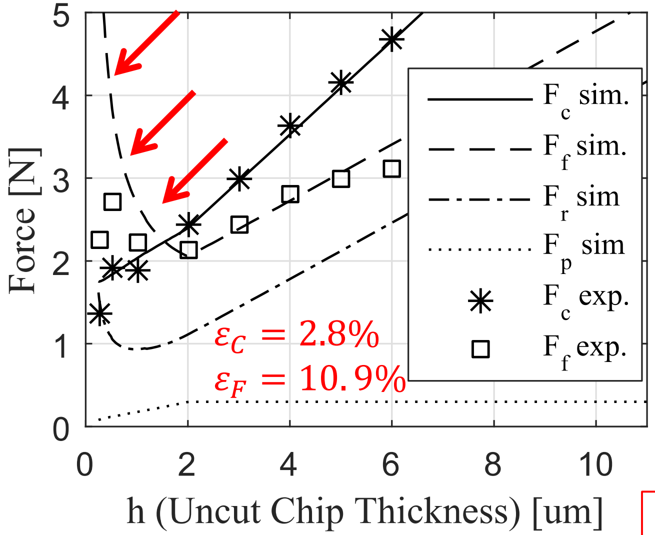


Results Force simulations



Constant Rake Angle

$\tau_y = 644\ MPa$
$R = 3.18\ kJ/m^2$
$R/\tau_y = 4.94 \times 10^{-6}$



Variable Rake Angle

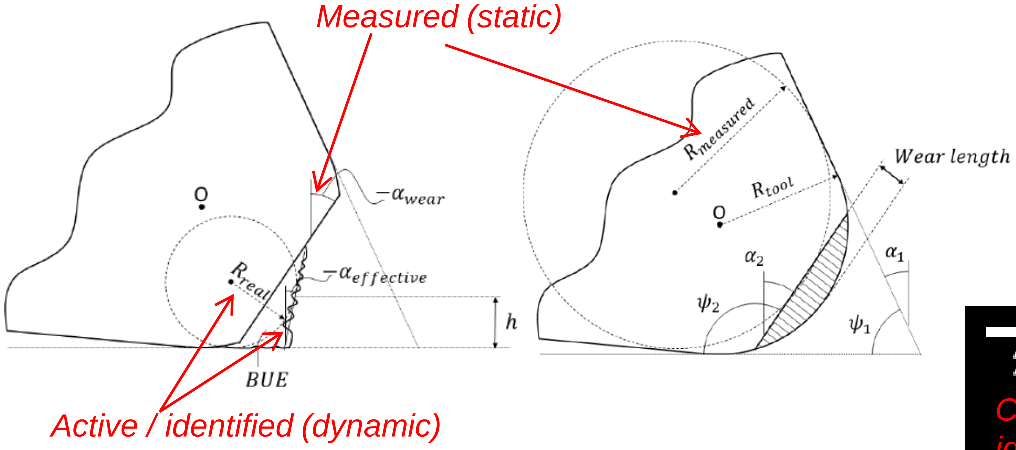
$\tau_y = 636\ MPa$
$R = 3.17\ kJ/m^2$
$R/\tau_y = 4.98 \times 10^{-6}$

Best results for identified parameters:

Parameter	Value
$r_e\ (\mu m)$	2
α_{tool} (°)	0
m (-)	0.94
λ (°)	1.5

Simulation results for variable rake angle over predicts feed forces.

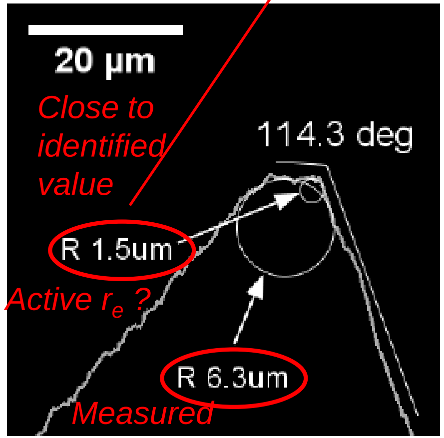
Results



Comparison of identified and measured parameters

	Val.	
$r_{effective}$ (μm)	2	Identified from model (dynamic)
$\alpha_{effective}$ (°)	0	
$r_{measured}$ (μm)	6.3	Static measurement
$\alpha_{measured}$ (°)	-34.3	

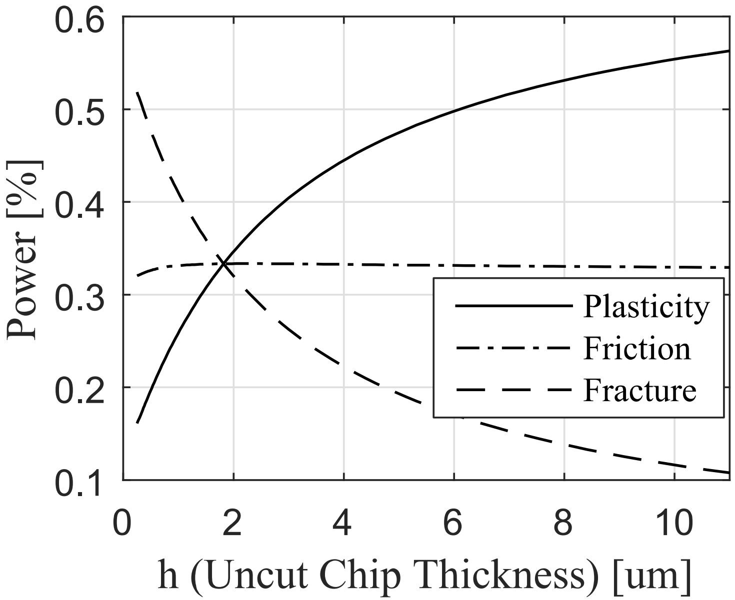
Some Identified parameters (r, α) did not perfectly match with measured values.



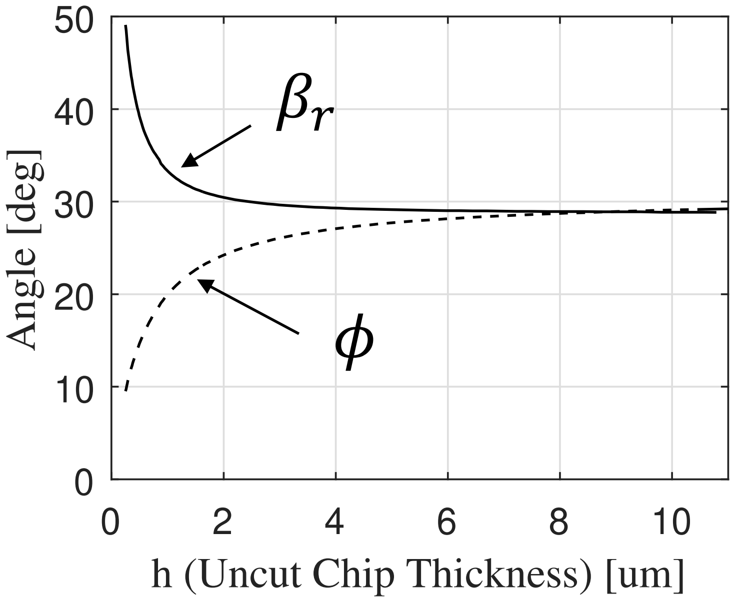
Example cutting tool profile measurement

Results

- Importance of fracture increases in lower feeds.



Power proportions for constant rake angle approach



Friction and shear angle values w.r.t. uncut chip thickness

Conclusion

- Effective rake angle and edge radius parameters have uncertainities, because of wear and material build up.
- Identifying effective rake angle correctly has importance on process outputs in the ploughing dominated region.
- Relative importance of fracture work is shown to be significant at uncut chip thickness values are comparable to edge radius.

Contact:

alp.aksin@bilkent.edu.tr
alp.aksin@roketsan.com.tr

BILKENT UNIVERSITY
MECHANICAL ENGINEERING DEPARTMENT

Micro System Design and Manufacturing Lab.

Thank you very much for listening…

Appendix

Table 2: Calculated angles, parameter Z and specific cutting pressure for uncut chip values.

	Variable α (changes w.r.t. r_e and h)					Constant $\alpha = 0°$				
h [μm]	Z [−]	ϕ [deg]	β_r [deg]	α [deg]	F_c/wh [N/m^2]	Z [−]	ϕ [deg]	β_r [deg]	α [deg]	F_c/wh [N/m^2]
0.25	20	5.1	14.3	-61.0	28053	19.8	9.5	49.1	0.00	24521
0.50	10.0	9.6	15.9	-48.7	14734	9.9	14.6	39.3	0.00	13393
1	4.9	16.6	19.5	-29.1	7946	4.8	20.2	33.2	0.00	7601
2	2.4	25.3	28.2	0.00	4735	2.4	24.4	30.4	0.00	4903
4	1.2	27.2	29.1	0.00	3505	1.2	27.1	29.3	0.00	3548
6	0.8	27.9	29.6	0.00	3078	0.8	28.2	29.0	0.00	3078