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FEM Simulation of Minimum Uncut Chip Thickness in Mechanical Microcutting

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Contents

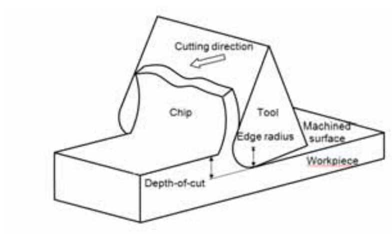
What is MUCT?

- **Definition**
  - **The minimum un-deformed thickness of the chip removed from a work surface at a cutting edge under perfect performance.**
  - **A chip will not be generated if the uncut chip thickness is less than a critical value, viz., MUCT.**

What is MUCT?

- **In Orthogonal Cutting**

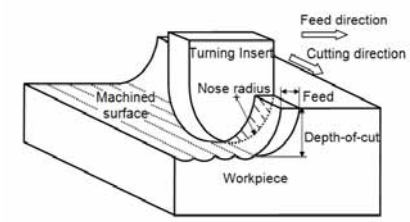
When depth of cut keeps decreasing till a critical value, there will no chip formation, material will be plowed under the cutting edge without forming a chip, this critical value will be the minimum uncut chip thickness.



What is MUCT?

- **In Micro-turning**

There exists a critical value of feed that beneath which will no chip formation. The critical value of feed is called MUCT.

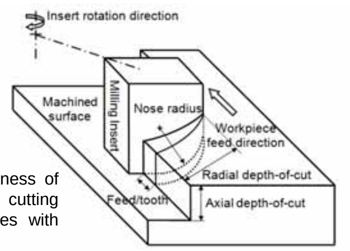


What is MUCT?

- **In Micro-milling**

With feed / tooth increased, there is a transition point from a plowing dominated to a shearing-dominated region which is defined as the minimum uncut chip thickness.

Feed / tooth: the thickness of chip material that each cutting edge of a tool removes with one pass.



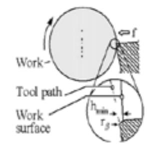
Why it is important to do research on MUCT

- **Effect of MUCT on cutting parameters**
  - ➢ Chip morphology
  - ➢ Cutting force
  - ➢ Cutting temperature
- **Effect of MUCT on surface integrity**
  - ➢ Surface roughness
  - ➢ Surface residual stress

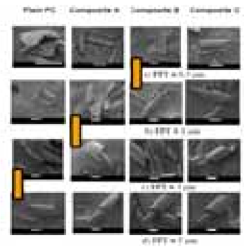
Effect of MUCT on cutting parameters

- **Chip morphology**

➢ **[Barry et al., 2001] In orthogonal cutting with any value of feed, the instantaneous value of the undeformed chip thickness increases from zero to the required value.**



➢ **Samuel et al. [2008] conducted micro end milling on carbon nanotube, found that chip transition from discontinuous to continuous chips in the range of feed-per-tooth values between 3-5um.**

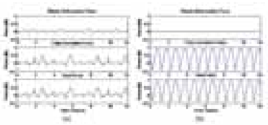


Effect of MUCT on cutting parameters

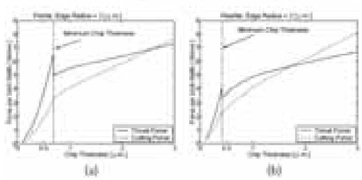
- **Cutting force**

➢ **[Liu et al., 2006] Due to MUCT, the micromachining process is affected by two mechanisms---chip removal and plowing/rubbing.**

➢ **[Vogler et al., 2004] The relatively small change in force magnitude with feedrate can be explained by MUCT effect in the micromilling force process.**



➢ **[Liu et al., 2004] Because of MUCT effect, the relationship between the cutting force and the chip load is highly nonlinear, which makes the dynamic behavior of the micro-end milling process strongly dependent on the feedrate.**



Effect of MUCT on cutting parameters

- **Cutting temperature**

➢ **The understanding of cutting temperature distribution can aid in addressing important metal cutting issues such as part surface integrity, tool life and dimensional tolerance under practical operating conditions (Huang and Liang, 2003).**

➢ **Liu et al. (2006) developed an iterative solution method to solve the normalized minimum chip thickness and the cutting temperature which accounts for the effects of thermal softening and strain hardening.**

$$T_1 = T_0 + \Delta T_1 \qquad R_T = \frac{V t_c}{\alpha}$$

$$\Delta T_1 = \frac{(1-\beta_1)(P_s + P_p)}{c\rho S V_c}$$

$$\beta_1 = \frac{1}{R_T \tan\theta} \operatorname{erf}\left(\frac{\sqrt{R_T \tan\theta}}{2}\right) + \left(1 + \frac{\sqrt{R_T \tan\theta}}{4}\right) \operatorname{erfc}\left(\frac{\sqrt{R_T \tan\theta}}{2}\right) - \frac{e^{-\frac{R_T \tan\theta}{4}}}{\sqrt{\pi}}\left(\frac{1}{R_T \tan\theta} + \frac{R_T \tan\theta}{2}\right)$$

The uncut chip thickness t_c was set equal to the minimum uncut chip thickness . But when the minimum uncut chip thickness is decided, the authors didn't investigate the minimum uncut chip thickness' effect on the cutting temperature

Effect of MUCT on surface integrity

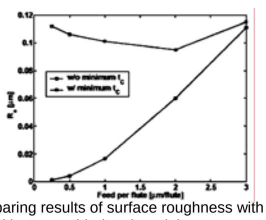
- **Surface roughness**

➢ **Brammertz (1961) proposed a model of the theoretical surface in finish turning, which takes into consideration of the minimum uncut chip thickness, it can be seen that the surface roughness will increase with the increase of h_{min}**

$$R_{zt}^{B} = \frac{f^2}{8r_\varepsilon} + \frac{h_{min}}{2}\left(1 + \frac{r_\varepsilon h_{min}}{2}\right)$$

➢ **Vogler et al. (2004) conducted a series end milling experiments on single-phase materials by changing feed rate from 0.25 to 3μm/flute with cutting edge radius 2.0 and 5.0μm, and built a new surface generation model considering the effect of minimum uncut chip thickness.**

$$y_{tc,min}(x) = y_{ta}(x) + \hat{n}(x)^{*} t_{c,min}$$



Comparing results of surface roughness with and without considering the minimum uncut chip thickness effect

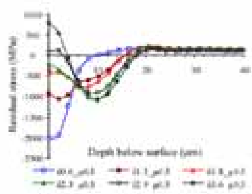
Effect of MUCT on surface integrity

- **Surface residual stress**

➢ **Residual stresses are known to cause poor surface integrity**

➢ **Guo et al. (2009) present a novel hybrid predictive model and found that ploughed depth is a major influencing factor in producing the machining-induced RS profile.**

When the ploughed depth is smaller than 2.3μm, there is compressive residual stress at the surface, but when the ploughed depth is larger than 2.9μm, tensile residual stresses occur at the surface. Therefore, it is reasonable to believe that the transition ploughed depth is in the range of 2.3 to 2.9μm.



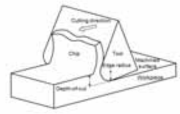
How to determine MUCT

- **Analytical Models of MUCT**
  - **Established analytical model**
  - **Characteristic of different analytical model**
- **Experimental Research about MUCT**
  - **Based on different cutting process: orthogonal cutting, turning, milling**
  - **Characteristic of Experimental Research**
- **FEM Simulation on MUCT**
  - **Friction model between Tool and Workpiece**
  - **Chip formation criterion**
  - **Model validation**
  - **Characteristic of FEM simulation**

How to determine MUCT

Analytical models

Literature	Analytical Model	Characteristic of analytical model	Process based on
(Basury at al., 1976)	$E_y = E_c$ $\theta^* + \pi \sin^2\left(\frac{\theta^*}{2}\right) = \tan\left(\frac{\theta^*}{2}\right)[(5.71 - 2\theta^*)\sin\theta^* - \cos\theta^* + 1]$	θ^* is the neutral point angle	Orthogonal cutting $\theta^* = 37.6°$
(Yuan et al., 1996)	$a_{cmin} = \rho\left(1 - \frac{F_y + \mu F_x}{\sqrt{(F_x^2 + F_y^2)(1 + \mu^2)}}\right)$	ρ- the edge radius μ- friction coefficient ratio of $\frac{F_y}{F_x}$ depends on the strength, the elongation and the friction coefficient of the workpiece and the position of the point along the cutting edge. empirical value is 0.8~1.0	Orthogonal cutting process $a_{cmin} = 0.322\rho$ When F_y=0.9F_x, μ=0.12 $a_{cmin} = 0.249\rho$ When F_y=0.9F_x, μ=0.26
(Son et al., 2005)	$t_m = r\left(1 - \cos\left(\frac{\pi}{4} - \frac{\beta}{2}\right)\right)$	β- friction angle a friction test had to be conducted to measure the friction coefficient	Orthogonal cutting Friction coefficient in the range of 0.05-0.5 t_m varies from 0.02-0.3μm



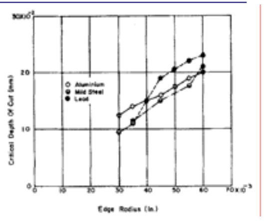
How to determine MUCT

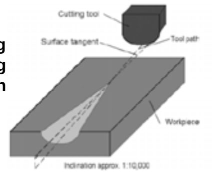
Analytical models

Literature	Analytical Model	Characteristic of analytical model	Process based on
(Liu et al., 2006)	$\lambda_n = \frac{h_r}{r_n} = \frac{tc_{min}}{r_e} = 0.5 - \frac{\tau_s}{\sigma}$ $\tau_s = \frac{0.427}{3} L_m \rho \ln\left(\frac{T_m}{T_2}\right)$ $\sigma = [A + B(\varepsilon)^n][1 + C\ln(\dot{\varepsilon})][1 - (\frac{T_1 - T_0}{T_m - T_0})^m]$	In order to obtain σ and τ_s, tool edge radius, the cutting temperature T_1 at the work/chip interface and T_2 at chip/tool interface, the strain ε, the strain rate $\dot{\varepsilon}$ are required.	Orthogonal cutting λ_n of Al6082-T6 is found around 0.4
(Wang et al., 2008)	$t_m = r\left(1 - \cos\left(\frac{\pi}{4} - \frac{\beta}{2}\right)\right)$ $\emptyset = \tan^{-1}\left(\frac{\gamma\cos\alpha}{1 - \gamma\sin\alpha}\right) = \beta$ $\gamma = \frac{t}{t_c}$	t-depth of cut t_c-chip thickness α-rake angle t_c has to be get by experiment	Orthogonal cutting
(Ikawa et al., 1992)	$t_b = f\sin\phi = \frac{F}{N}\sin\emptyset$	ϕ-the tool setting angle, F-the feed velocity (μm·min⁻¹) N-the spindle speed (rpm)	Turning process
(Kim et al., 2004)	$p(h_m, f_t, \theta) = roundup\left(\frac{h_m}{f_t \cdot \sin(\theta)}\right)$	p-period of variation f_t-feed per tooth θ-angle of interest	Milling process

Experimental Research about MUCT

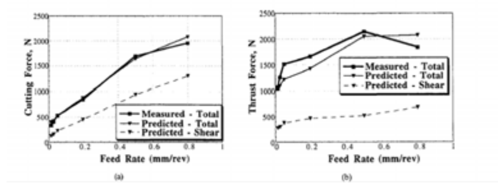
- **Experimental Methods (based on orthogonal process)**
  - [Basuray et al., 1977]
    By present an ever increasing depth of cut, and observed through microscope when chip formation.
  - [Fang et al., 2003]
    Conducted experiments using diamond cutting for machining single crystal silicon with increasing depth of cut.





Experimental Research about MUCT

- **Experimental Methods (based on turning process)**
  - [Waldorf et al., 1998] **Taking a series of experiments on 6061-T6 aluminum using tools with different edge radii.**



Experimental Research about MUCT

- **Experimental Methods (based on milling process)**
  - [Liu et al., 2006] **By seeking and measuring the unique characteristics of the sudden surface height change.**

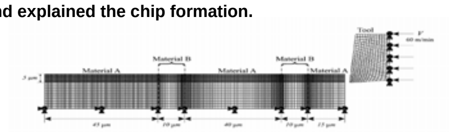
  - [Samuel et al., 2008] **Conducted micro end milling experiments on carbon nanotube and found that chips transition from discontinuous to continuous chips in the range of feed-per-tooth values between 3-5μm.**
  - [Dhanorker et al., 2006] **Conducted meso scale milling experiments by varying feed rate and MUCT was found when feed/tooth was around 0.53μm/tooth.**

Experimental Research about MUCT

- **Characteristic of Experimental Research**
  - **Experimental method for estimation of MUCT is tedious by changing depth-of-cut, feed rate, feed/tooth.**
  - **The experimental method need expensive equipments.**
  - **The results can be affected by experimental uncertainties.**

FEA Simulation on MUCT

- **Based on 2D Orthogonal Cutting**
  - [Vogler et al.,2004] **Used a customized FEM code developed by Chuzhoy et al., to determine MUCT for ferrite and pearlite metal.**
  - Simoneau et al. [2006] **assigned different hardness parameters to different metal-phase components of steel and explained the chip formation.**



  - [Ozel et al., 2006] **Predicted the chip formation and temperature fields for meso/microscale millig.**
  - [Woon et al. 2008] **Discussed the relationship between the ratio of MUCT to tool edge radius and chip formation mechanism**

FEA Simulation on MUCT

- **Friction model between Tool and Workpiece**
  - [Karpat et al., 2008] **Pointed out that usually a constant friction factor or coefficient of friction is used to define friction model.**
  - [Yan et al., 2009] **Material deformation in cutting is also influences by tool-workpiece friction. There are two types of friction, namely, Coulomb friction and shear friction. The friction between the tool and chip in this work is of the shear type.**
  - [Simoneau et al., 2006] **Pointed out that contact at the tool-chip interface uses a penalty contact algorithm with an estimated Coulomb friction coefficient of 0.2.**

FEA Simulation on MUCT

- **Chip formation criterion**
  - **Chip separation criterion**
    - ✓ [Weber et al., 2007] [Lai et al., 2008] **used the phenomenological model proposed by Johnson and Cook [1985], which describes the failure of ductile materials. Any finite element is deleted, when its damage parameter D reaches unity.**
    - ✓ [Ceretti et al., 1996] **The chip flow model is based on the damage criteria that combination the traditional damage criteria with a stress based or a geometric criterion.**
  - **ALE (Arbirary Lagrangian Eulerian) method**
    - ✓ **It combines the features of pure Lagrangian and Eurerian analysis and is performed in adaptive meshing domains.**

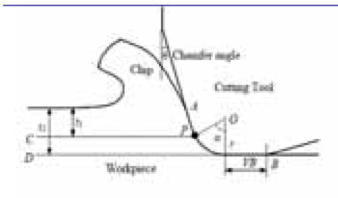
FEA Simulation on MUCT

- **Model validation**
  - **[Lai et al., 2008] conducted extensive experiments of OFHC copper micro scale milling, and got good agreements between the predicted and the experimental results.**
  - **[Vogler et al., 2004] analyzed the surface profile of the workpiece after experiments, found that due to MUCT, the surface profile contains a saw tooth appearance.**
  - **[Karpat and Ozel, 2008] conducted bar turning experiments to compare uniform and variable edge preparations with the results of 3-D finite element analysis.**
  - **[Wang et al., 2009] in order to validate the simulated chip formation, the micro-milling experiment was conducted on a 3D micro machine tool.**

FEA Simulation on MUCT

- **Characteristic of FEM simulation**
  - **An efficient tool to study the metal cutting process.**
  - **Allow for considering process details such as material properties that analytical and experimental method cannot handle.**

FEM of Materials properties' effect on MUCT



$$t_2 - t_1 = r - r\cos\alpha$$

- There is no doubt that the minimum uncut chip thickness is affected by tool edge radius *r* and stagnation angle α.
- Does materials properties have effect on the stagnation angle?
- Five materials with different elastic modulus Copper, AISI 4340, Al 7050, Ti-6Al-4V, and IN 718 were selected to investigate the influence of material properties on MUCT by FEM simulation.

FEM of Materials properties' effect on MUCT

- **Materials properties**

Material Properties	Al 7050 [Fu et al., 2006]	Copper [Johnson et al., 1983]	AISI4340 [Johnson et al., 1983]	Ti6Al4V [Peirs et al., 2010]	Inconel718 [Demange et al., 2009]
Density (kg/m^3)	2750	8960	7830	4428	8190
Poisson ratio	0.33	0.34	0.29	0.342	0.284
Elastic modulus (GPa)	70.3	124	200	114	211
Melting point (°C)	490-630	1083	1520	1653	1300
Thermal conductivity (W/m-k)	167	386	38	6.7	11.4
Thermal expansion ($10^{-6}/k$)	23.6	17	12.3	8.6	13
Specific heat (J/kg K)	850	383	477	580	435
Flow stress (MPa)	697	382	1302	1552	1979
Elongation (%)	11	13.5	13	14	12
Shear modulus (GPa)	26.9	48	80	44	77.8

FEM of Materials properties' effect on MUCT

- **Materials' constitutive model**

➢ The accuracy of the finite element analysis is severely dependent on the accuracy of the material mechanical properties.

➢ Johnson-Cook model describes the flow stress of work material with the product of strain, strain rate and temperature effects.

$$\sigma = [A + B(\bar{\varepsilon})^n]\left[1 + C\ln\left(\frac{\dot{\bar{\varepsilon}}}{\dot{\bar{\varepsilon}}_0}\right)\right]\left[1 - \left(\frac{T - T_{room}}{T_{melt} - T_{room}}\right)^m\right]$$

FEM of Materials properties' effect on MUCT

- **Materials constants for JC model**

Literature	material	A (MPa)	B (MPa)	n	C	m	Testing conditions	Strain rates (s^{-1})
Yield stress: 441MPa [Han et al., 2006]	Al 7050	490	207	0.344	0.005	1.8	SHPB	600-3500
Temperatered at 427℃, 60mins Hardness: F-30 [Johnson et al., 1983]	Copper	90	292	0.31	0.025	1.09	Torsion tests	451-464
Austenitized quenched tempered Hardness: C-30 [Johnson et al., 1983]	AISI 4340	792	510	0.26	0.014	1.03	Torsion tests	570-650
Low-cost material [Meyer et al., 2001] Yield stress 896MPa	Ti-6Al-4V	896	656	0.5	0.0128	0.8	SHPB	0.0001-2150
Remelted material IN-718 [Kobayshi et al., 20098] Yield stress: 330MPa	IN 718	980	1370	0.164	0.02	1.03	SHPB	8500-12500

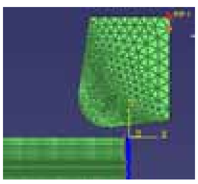
FEM of Materials properties' effect on MUCT

- **Analysis step**

➢ **Initial step**

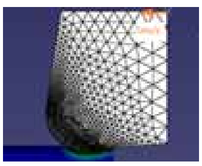
➢ **Tool-workpiece contact step**

✓ There is 5μm distance between the workpiece and cutting tool. The cutting tool was given a displacement and then got contact with the workpiece.



➢ **Steady-state cutting process**

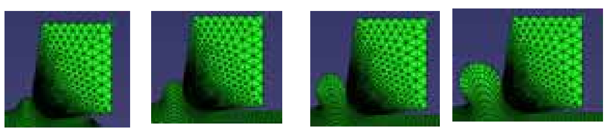
✓ In cutting step, the cutting tool was given a velocity of -5m/s in the X direction



FEM of Materials properties' effect on MUCT

- **Time Criterion**

➢ With time increases, material increases in front of cutting tool. It is necessary to introduce Time Criterion to decide the value of MUCT.



➢ [Burns et al., 2009] Time interval required to deform an element of the work material into a corresponding element of the chip is $\Delta t = d / V_N$, d is shear zone thickness, and V_N is the normal speed of the work material, and $V_N = V\sin\varphi$, φ is shear plane angle, V is cutting speed

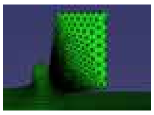
When V=5m/s, time interval Δt is proposed to be 1×10^{-5} s

- **Chip formation judgment criterion**

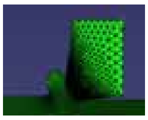
➢ When materials in front of cutting tool stop the statement of plowing, instead of increasing in the direction of parallel to the rake face of cutting tool is taken as chip formation

FEM of Materials properties' effect on MUCT

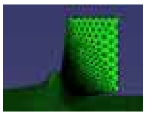
- **Results of FEM simulation**



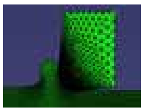
Copper
depth-of-cut is 2.5μm



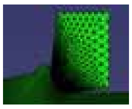
AISI 4340
depth-of-cut is 3μm



Al 7050
depth-of-cut is 2.8μm



Ti-6Al-4V depth-of-cut is 3.5 μm



IN718 depth-of-cut is 4μm

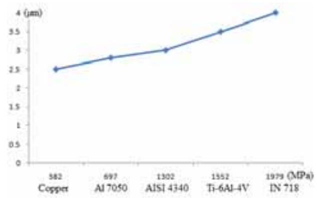
FEM of Materials properties' effect on MUCT

- **Results of FEM simulation**

Materials	MUCT
Copper	2.5 μm
Al7050	2.8 μm
Ti-6Al-4V	3.5 μm
AISI4340	3 μm
IN718	4 μm

FEM of Materials properties' effect on MUCT

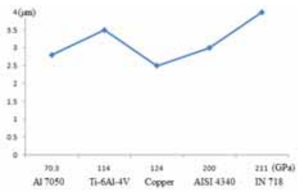
- **Results discussion**
  - **Relationship between materials' flow stress and MUCT**



- When ε is set to be 1, the flow stress σ_{JC} for the five different materials is as follows: σ copper =382 MPa; σ 4340=1302 MPa; σ Al 7050 =697 MPa; σ Ti-6Al-4V =1552 MPa; σ IN 718 =1979 MPa
- It can be seen that the MUCT increases with the flow stress.

FEM of Materials properties' effect on MUCT

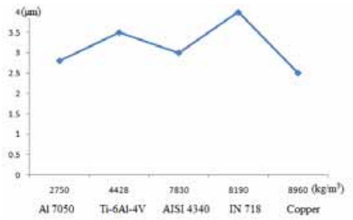
- **Results discussion**
  - **Relationship between materials' elastic modulus and MUCT**



- ✓ The value of MUCT decreases with elastic modulus increases, when elastic modulus increases to a certain value, the value of MUCT begins to increase.
- ✓ It seems that the elastic modulus has important influence on MUCT.

FEM of Materials properties' effect on MUCT

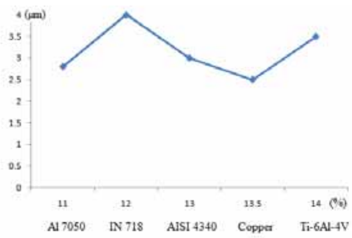
- **Results discussion**
  - **Relationship between material density and MUCT**



- ➢ No consistent concern between material density and MUCT

FEM of Materials properties' effect on MUCT

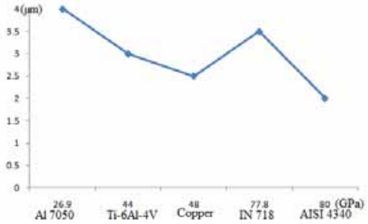
- **Results discussion**
  - **Relationship between material elongation percentage and MUCT**



- ➢ No consistent concern between material elongation percentage and MUCT.

FEM of Materials properties' effect on MUCT

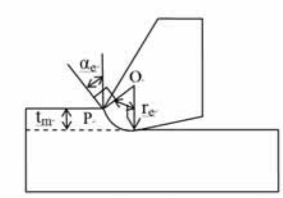
- **Results discussion**
  - **Relationship between material shear modulus and MUCT**



- **No consistent concern between material shear modulus and MUCT.**

FEM simulation of rake angle effect on MUCT

Point O is the center of cutting edge, point P is the stagnation point, αe is effective rake angle, β is stagnation angle, tm is the minimum uncut chip thickness, re is tool edge radius. MUCT can be expressed as tm=re (1-cosβ).

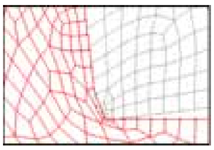


$$\alpha + \gamma = \frac{\pi}{2}$$

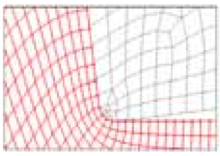
$$\alpha = sin^{-1}\frac{(r_e - t_m)}{r_e}$$

FEM simulation of rake angle effect on MUCT

During adaptive meshing, mesh-smoothing algorithms based on minimizing element distortion tend to reduce the mesh refinement in area of concave curvature.
As shown in Figure (a), the natural reduction in mesh refinement of areas leads cutting tool permeate into the workpiece, to prevent this situation, solution-dependent meshing is used to focus mesh gradation toward these areas automatically by defining the curvature refinement weight αc a high value, for example, αc=1 as shown in Figure (b).



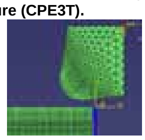
(a) α_c=0

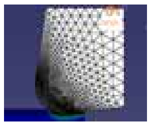


(b) α_c=1

FEM simulation of rake angle effect on MUCT

The workpiece uses four-node plane strain thermally coupled quadrilateral, bilinear displacement (CPE4RT). The cutting tool used three-node plane strain thermally coupled triangle, linear displacement and temperature (CPE3T).





(a)initial step of simulation process (b) cutting step of simulation process

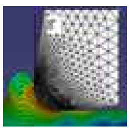
Material properties	Copper	Cutting tool
Density (kg/m^3)	8960	14900
Poisson ratio	0.34	0.22
Elastic modulus (GPa)	124	619
Thermal conductivity (W/m-k)	386	86
Thermal expansion (10^{-6}/°K)	17	5.6

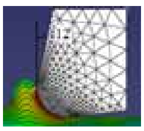
Orthogonal cutting parameters

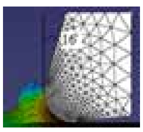
Cutting speed, V_c (m/s)	5
Tool rake angle, α (degree)	8, 12, 16
Tool clearance angle (degree)	6
Tool edge radius, ρ (μm)	15
Friction coefficient	0.2

FEM simulation of rake angle effect on MUCT

It can be seen that when the nominal rake angle is 8°, 12°, and 16°, the corresponding minimum uncut chip thickness is 2.5 μm, 2 μm, and 1.8 μm respectively.
It is found that as nominal rake angle increases, the minimum uncut chip thickness decreases. This is because as the rake angle increases, the cutting force is less ploughing dominant and chip can be formed easily.

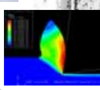




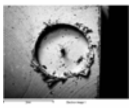


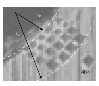
(a) 8°, MUCT 2.5μm (b) 12°, MUCT 2 μm (c) 16°, MUCT 1.8μm

Facilities for micro machining at SDU



Micro sensor





Micro nozzle

Conclusions

- Minimum Uncut Chip Thickness (MUCT) has different representations in orthogonal cutting, turning and milling operations.
- MUCT is very important due to its effects on cutting parameters and surface integrity
- Material properties such as flow stress, elastic modulus, density, elongation percentage, and shear modulus have deep effects on the MUCT.
- Tool geometries such as rake angle have great influence on the MUCT.
- The FEM simulation results need experiment validation.

山东大学 SHANDONG UNIVERSITY

QUESTIONS?

THANK YOU!

THE UNIVERSITY OF ALABAMA