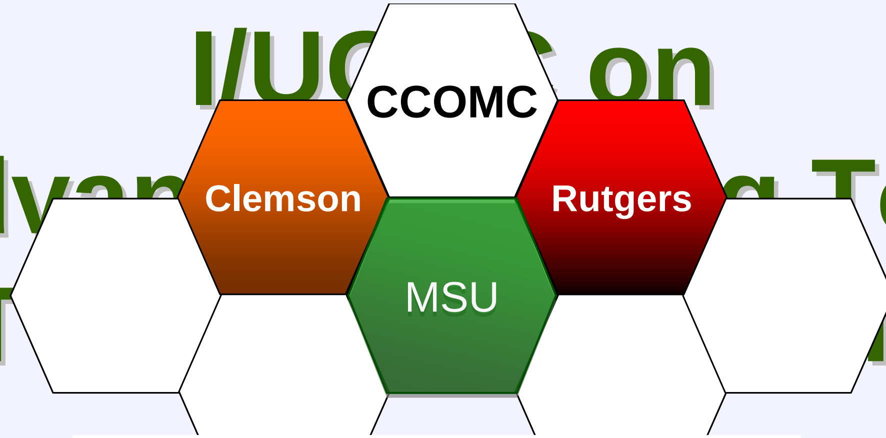
Center for Advanced Cutting Tool Technology
Industry/University Coorperative Research Center.

I/UC on Adv Tool T)



Ceramic, Composite and Optical Materials Center

Patrick Kwon
Mechanical Engineering
Michigan State University
East Lansing, Michigan
pkwon@egr.msu.edu
(517) 355-0173

Active & Prospective Members

- 1. Boeing, Seattle, WA
- 2. Fraunhofer CCL, East Lansing, MI
- 3, 4. Los Alamos National Lab, NM
- 5. Diamond Innovation/Valenite, Columbus, OH
- 6. ARMY ARDEC
- GM Powertrain
- Pratt & Whitney
- Caterpillar, Peoria, IL
- General Dynamic, St. Petersburg, FL
- Ford Motor Company
- Nexteer (Delphi)
- General Electric

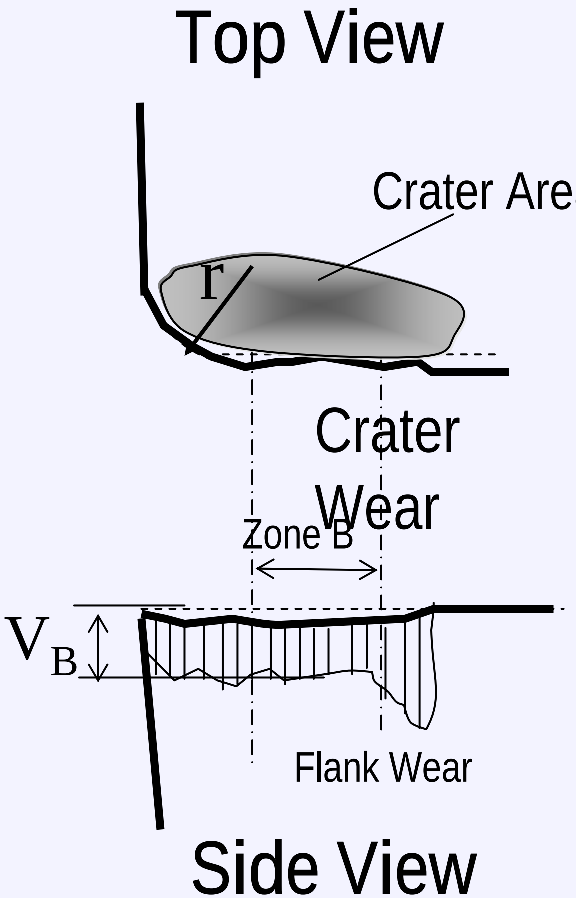
Current Projects

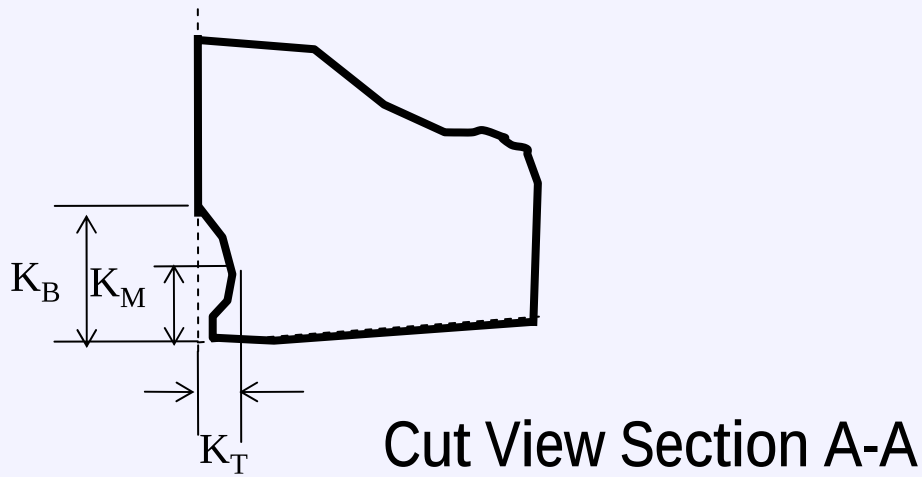
- Drilling of Composite/Metal Stack (Boeing, New Tech Ceramic & Fraunhofer)
  - Carbides, PCD & Coated Carbides
- Soft Machining (LANL & Valenite)
  - Adhesion
- Machining Titanium (ARMY-ARDEC & DI)
  - Tool Wear mechanisms
- Advanced Cutting Tool Systems (LANL-Fraunhofer)
  - Stacking sequence & thickness of Multi-layer Coatings
- MQL with Nanoenhanced-Lubricant (UNIST & XG Science)
- Many other projects are possible with other faculty at MSU.

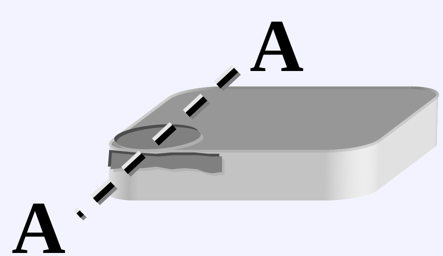
Tool Wear Approach

Still, an empirical approach

$$Taylor's\ Model: V^a d^b f^c = \text{constant}$$







- K_B = Crater Width
- K_M = Crater Center Distance
- K_A = Crater Area
- K_T = Crater Depth
- V_B = Wear Land Width
- r =Radius of Cutting Edge

Possible Wear Mechanisms

Mechanical wear

- **Abrasive wear**

- The sliding and rolling of hard second phase on the work/tool materials interface

- Delamination Wear

- Continual loading leads to subsurface cracks propagation

- **Adhesion** (Al)

- Welding of asperity junctions

Thermochemical wear

- **Dissolution Wear**

- Thermally activated mechanisms - Atomic transport across the interface

- **Diffusion wear**

- The component of tool materials can be diffused into chips

- **Chemical reaction** (Ti)

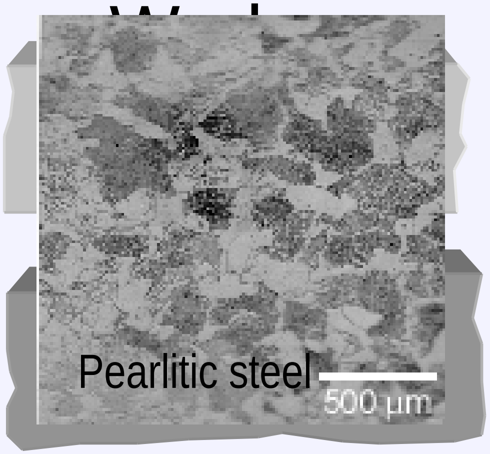
- Chemical reaction between tool and work material

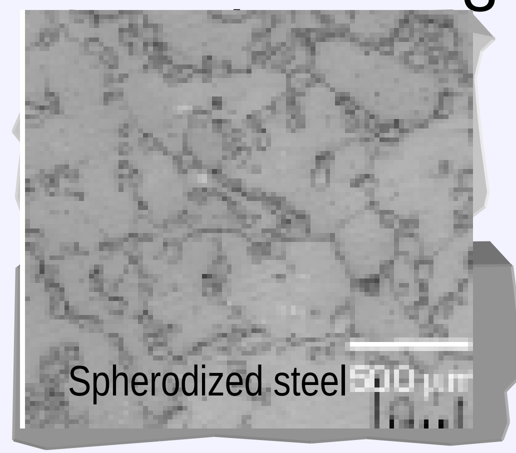
- Thermomechanical fatigue

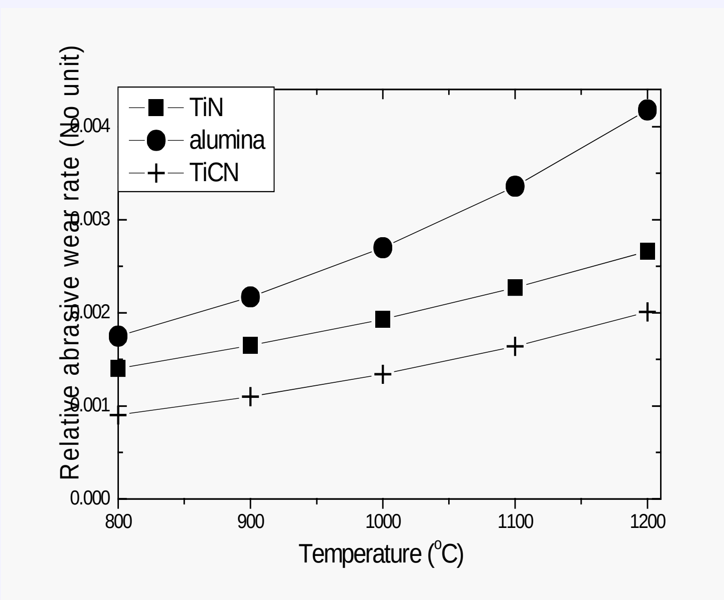
Abrasive Wear Models

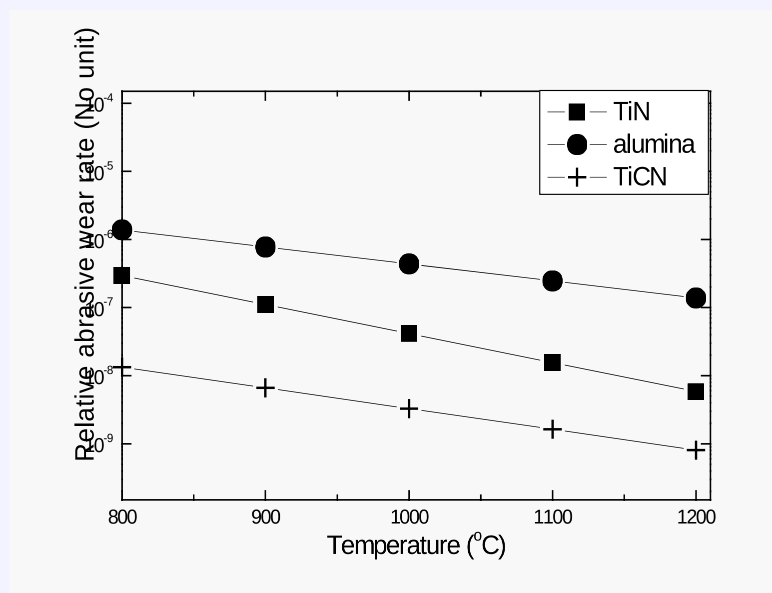
2-body Wear

3-body Wear









Amount of Abrasives: Compositions of Steels

(All in wt%)

	C	Mn	P	S	Si	Ni	Cr	Mo
1018	0.21	0.70	0.02	0.03	0.21	0.07	0.13	0.02
1045	0.48	0.74	0.01	0.04	0.27	0.05	0.08	0.02
1070	0.68	0.78	0.01	0.02	0.22	0.04	0.17	0.02
1018 (S)	0.16	0.83	0.01	0.03	0.20	0.01	0.08	0.01
1045 (S)	0.48	0.74	0.01	0.04	0.27	0.05	0.08	0.02
1065 (S)	0.64	0.80	0.01	0.01	0.28	0.07	0.15	0.02
1095 (S)	0.89	1.02	0.02	0.03	0.31	0.15	0.32	0.14

- Round Bar stocks: nominally of diameters between 3” and 6” and length about 2-1/2' initially.

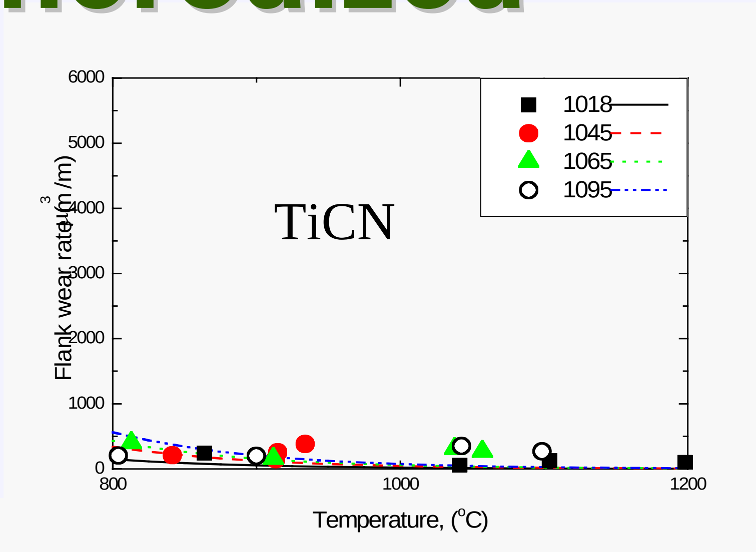
Flank Wear - Spherodized

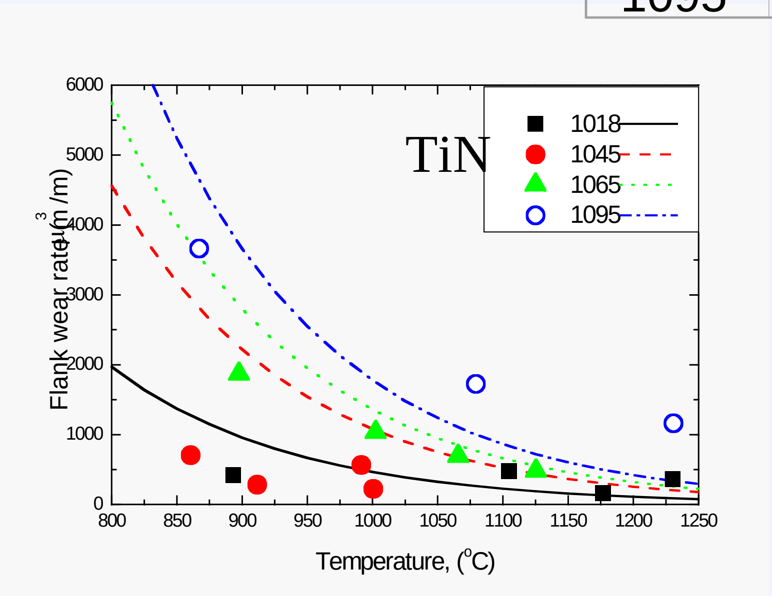
Flank Wear Rate

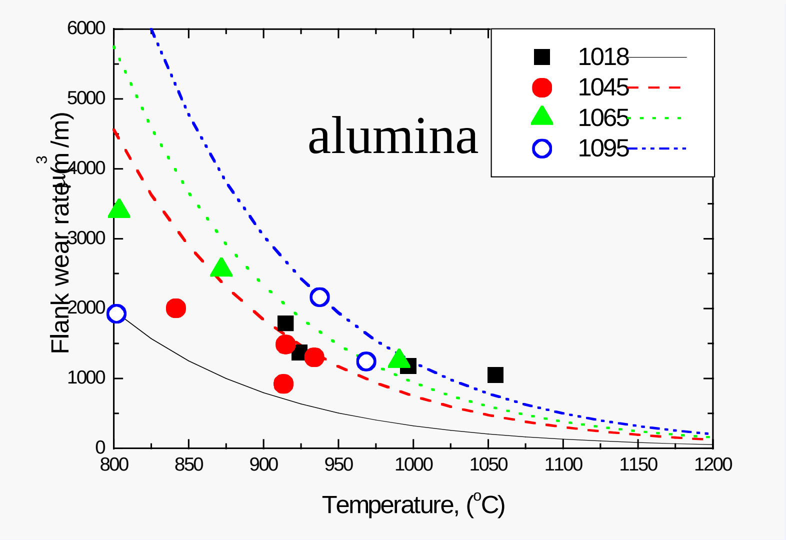
$$= 1.166A(P_a^{(n-1)})/P_t^n$$

Area fraction, A

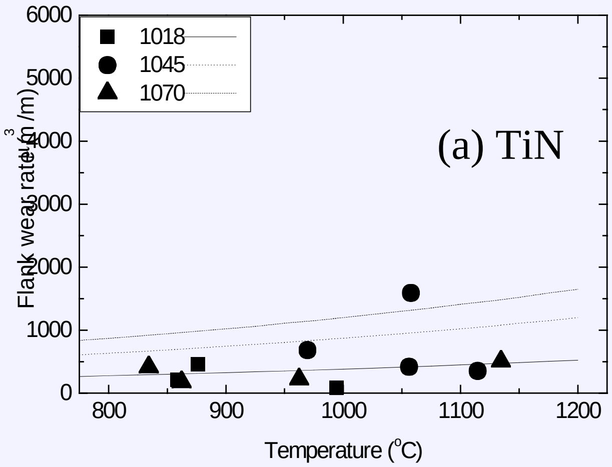
steel	A
1018	0.07
1045	0.16
1065	0.21
1095	0.27

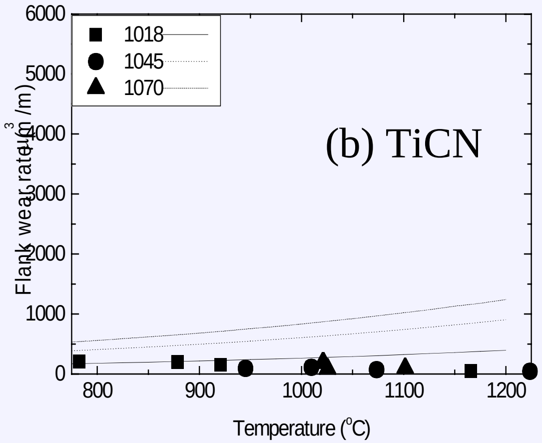


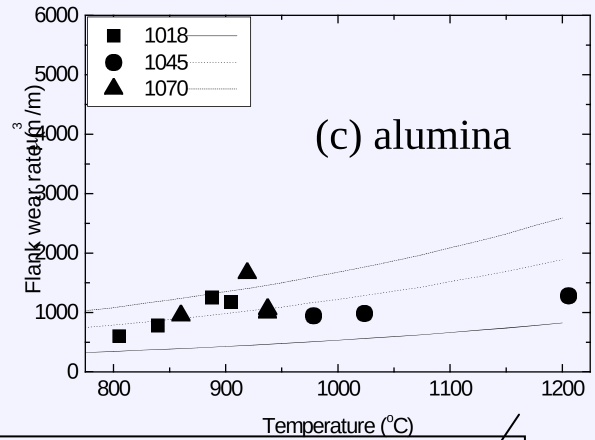




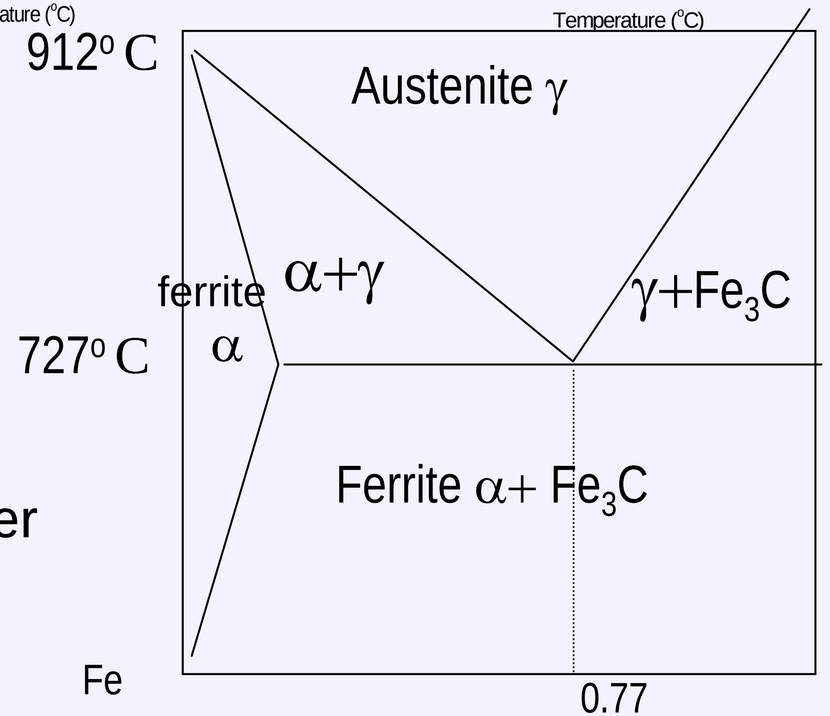
Flank Wear - Pearlitic







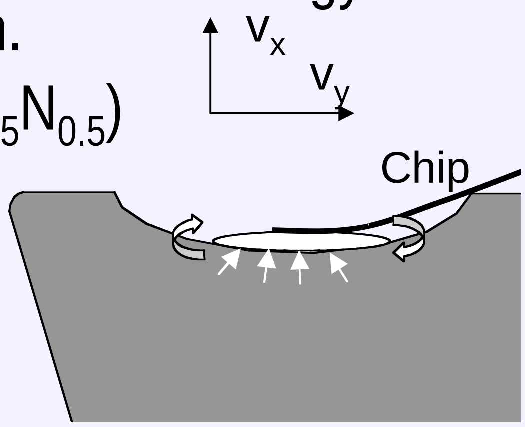
- The Inadequacy of 2-body Abrasive Wear Model
  - TiCN – too low wear
  - No cementire effect - Phase Transformation
  - 4340 & 52100 steels – white layer



Dissolution Wear Model

The material pair in sliding will dissolve to each other if the free energy of the material pair decreases by the formation of solution.

Dissolution wear rate for tertiary coating, $A_xB_yC_z$ ($Ti_1C_{0.5}N_{0.5}$) (Kramer & Suh, 1980; Kramer & Kwon, 1985)



Atomic transport across the interface

$$BMV^{0.5}\, C_{AxByCz}$$

B = the dissolution wear coefficient

M =molar volume of the coating material in cm^3/mol

V =cutting speed (m/min)

Solubility $$C_{A_xB_yC_z} = \exp\left[\frac{\Delta G_{A_xB_yC_z} - x\Delta G_A^{xs} - y\Delta G_B^{xs} - z\Delta G_C^{xs} - RT(x\ln x + y\ln y + z\ln z)}{(x+y+z)RT}\right]$$

$\Delta G_{A_xB_yC_z}$ = free energy of formation

ΔG_i^{xs} = excess free energy of i component

R = gas constant

T = temperature (K)

Dissolution Wear Rate

Tool Materials	Predicted Relative Wear Rate		Estimated Time for 25μm of wear
ZrO_2	0.0000367	26.053	26 month
Al_2O_3	0.00124	27.051	23 days
TiO_2	0.00313		21 hr
HfN	0.680		60 min
HfC	1.	1	41 min
TiN	5.92		6.9 min
TiC	12.8		3.2 min
BN	57.0		43 sec
WC	332.	0.824	7.4 sec
Diamond	445	0.227	5.5 sec
	At 1300° C into iron	At 1100° C **into Ti**	

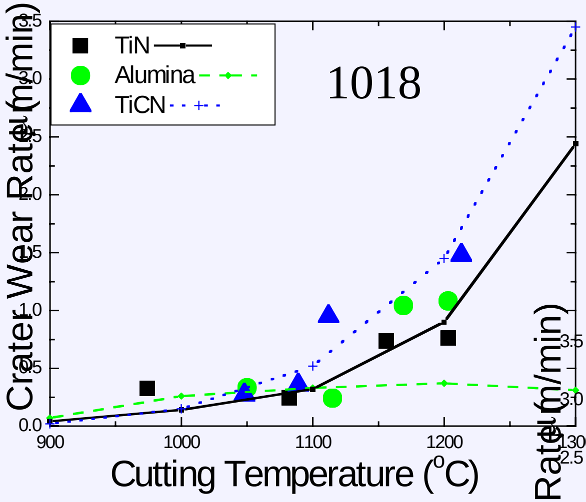
Crater Wear – Pearlitic

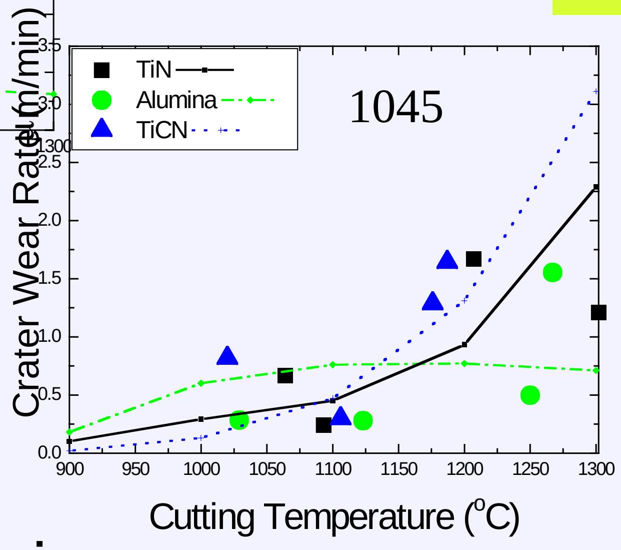
$$\text{Crater Wear Rate} = K_{abs} A V \left(P_a^{(n-1)}/P_t^{n}\right) + K_{dis}(1-A) M V^{0.5} C_{AxByCz}$$

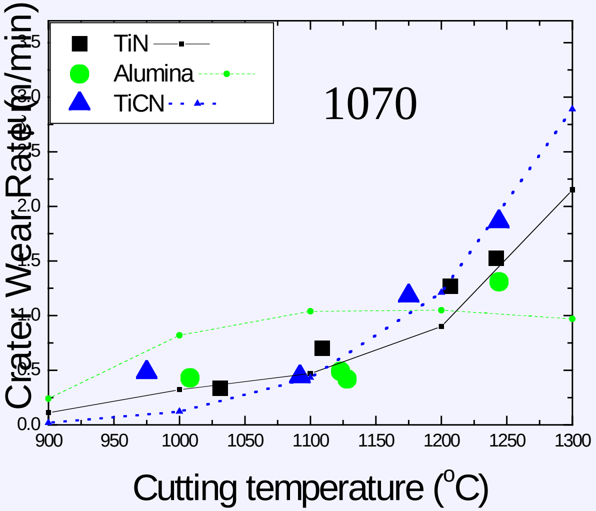
3-body Abrasive Wear | Dissolution Wear

Cutting coefficient, K_{abs}	Cutting coefficient, K_{dis}
145	31

Dissolve into Austenite Phase



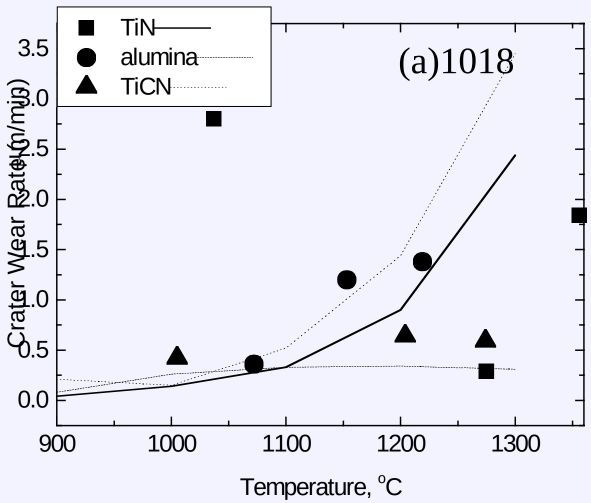


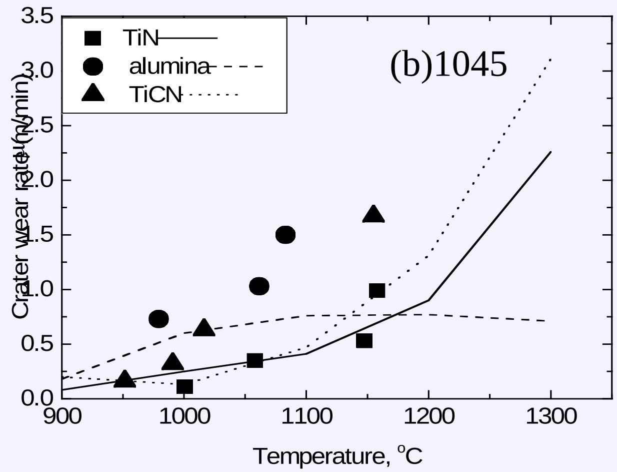


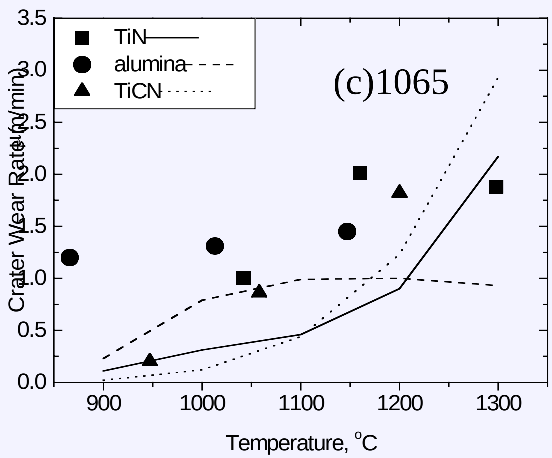
Problem with Alumina

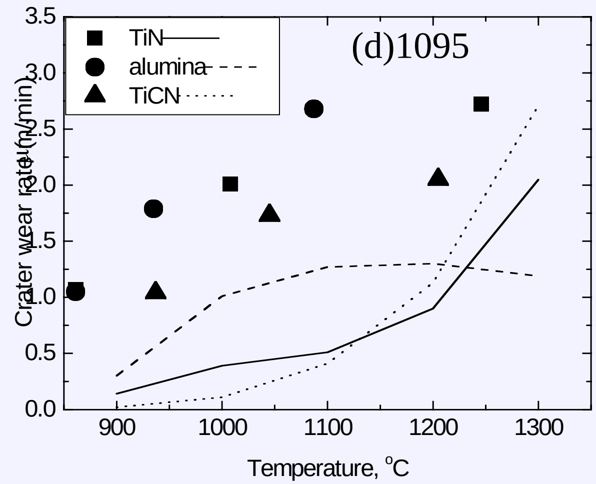
Crater Wear - Spherodized

Dissolve into ferrite Phase





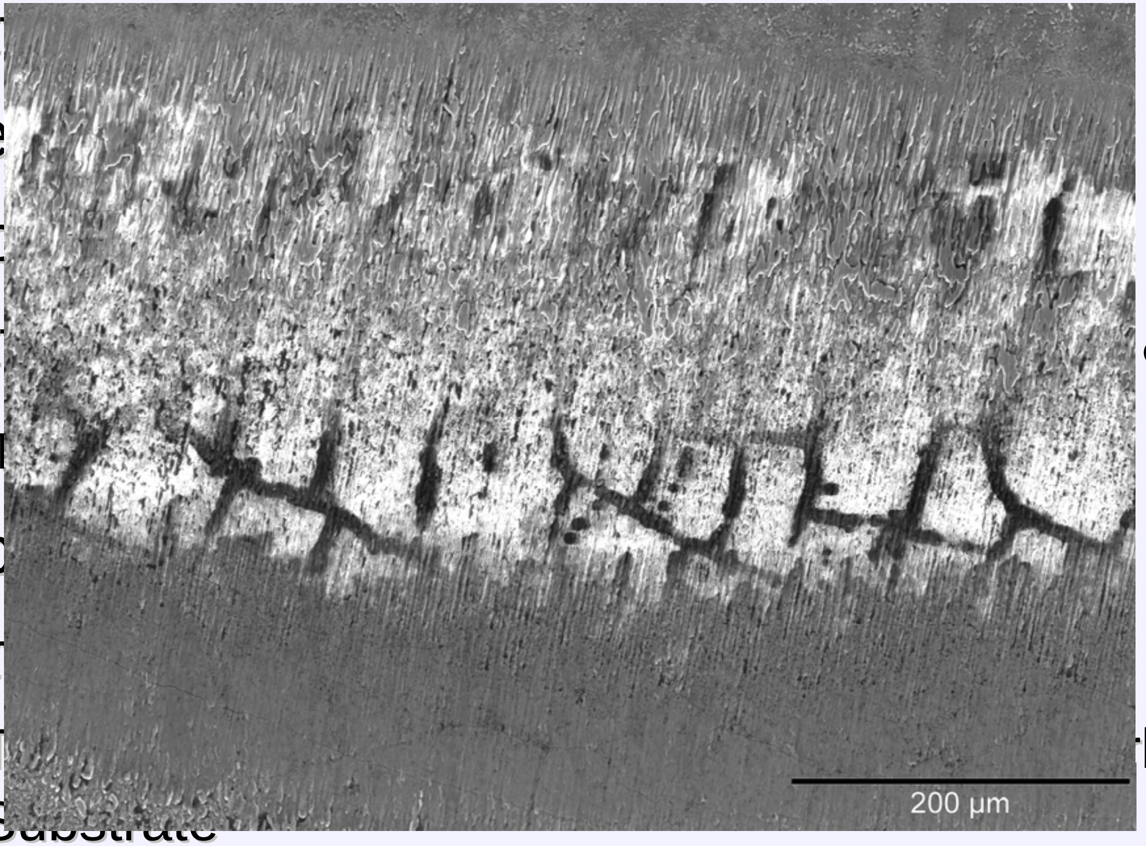




High Vanadium

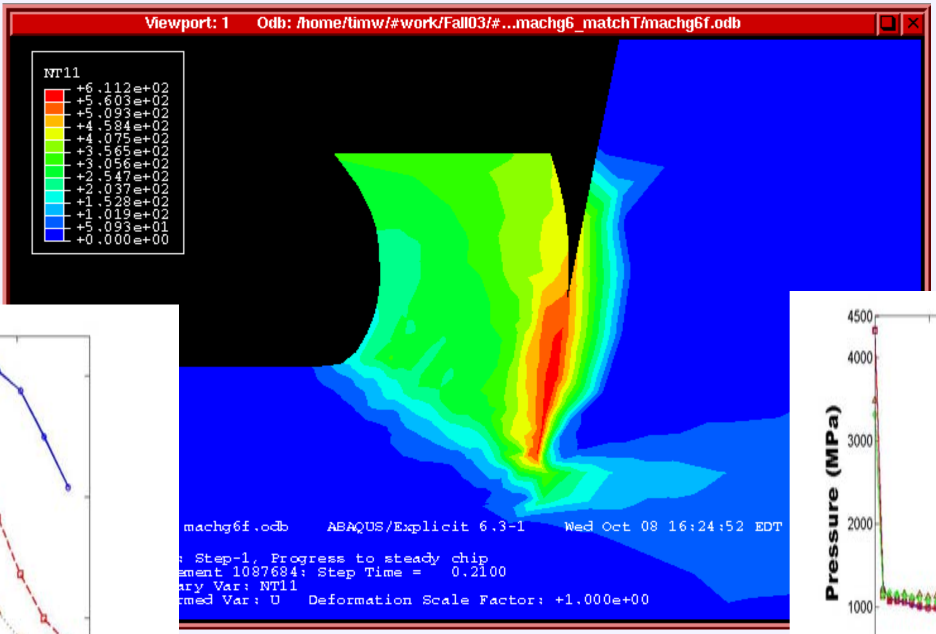
Effectiveness of Multi-layer coating (LANL)

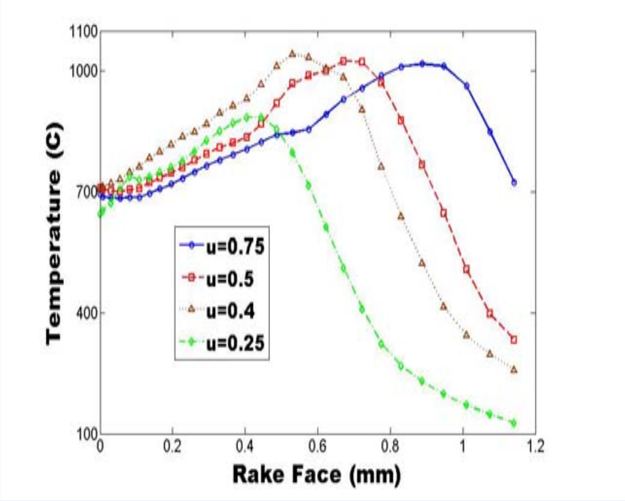
- **Experiments -** Turning AISI 1045 Steels
  - Cut
  - Fee
  - Dep
  - Cut & 480s.
  - Wor
  - App
  - Cut
    - T bide Substrate

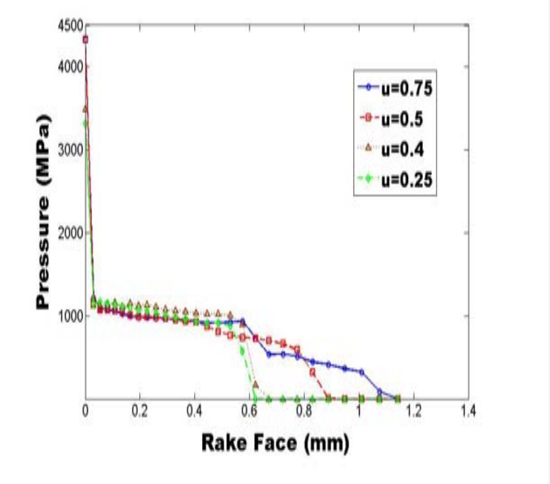


FE simulation - ABAQUS Modeling

- Arbitrary Lagrangian and Eulerian (ALE) Formulation
  - Tool and Work Material (Johnson-Cook Model for 1045 steels)
- Constitutive & Friction models





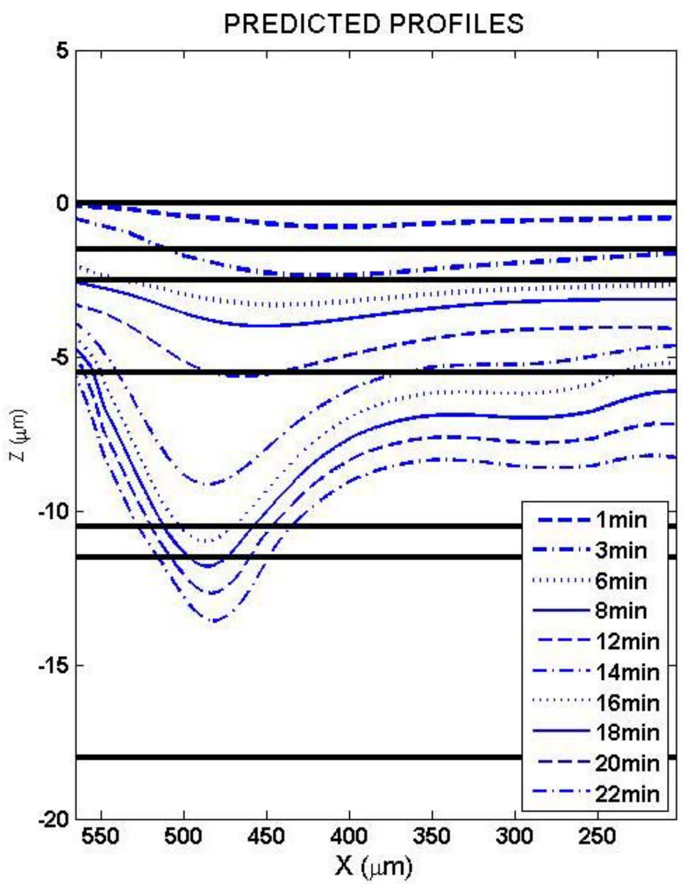


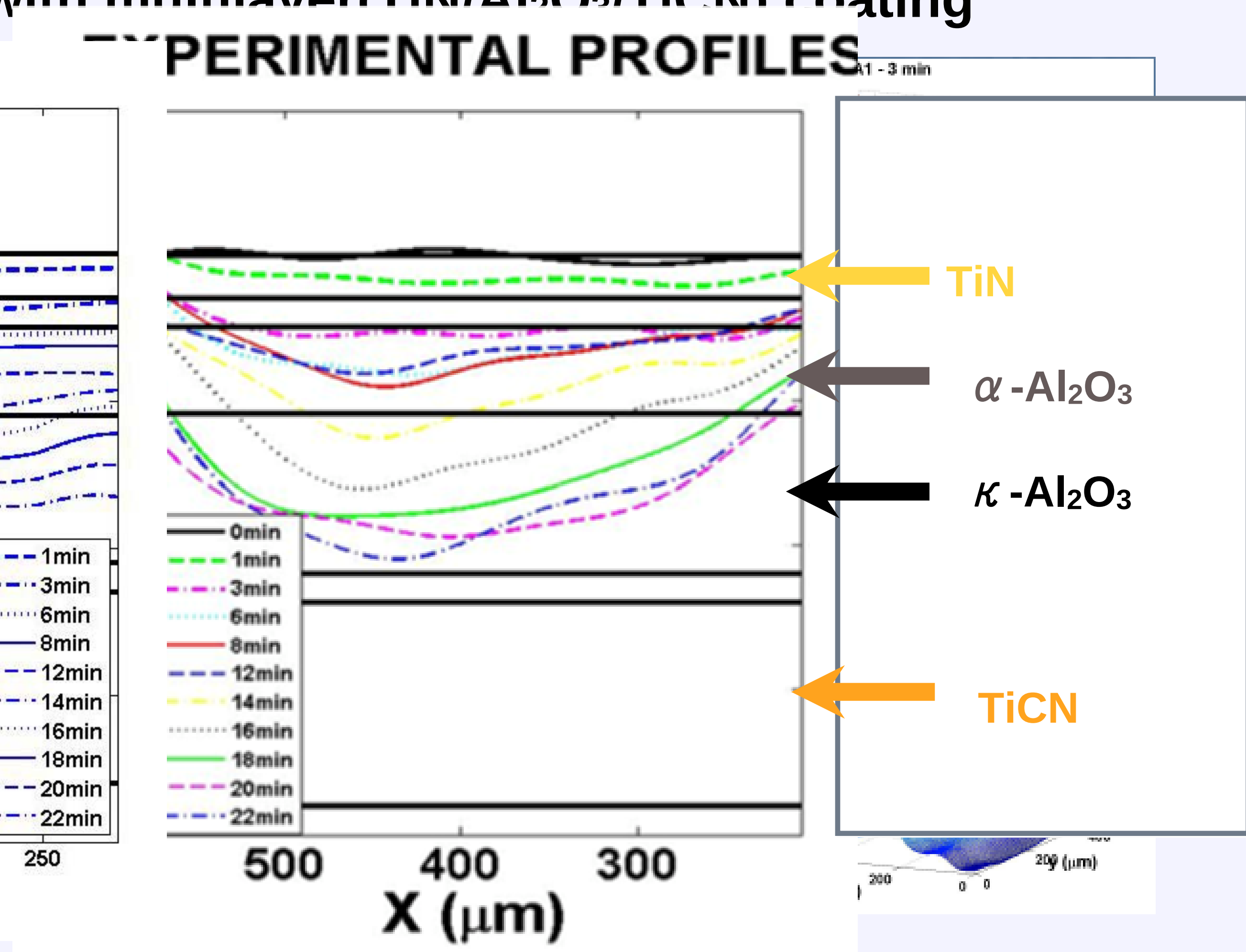
Rake Face

Contact Length

Crater Wear Summary

Tuning of 1045 steel with multilayer(TiN/Al_2O_3/TiCN) coating



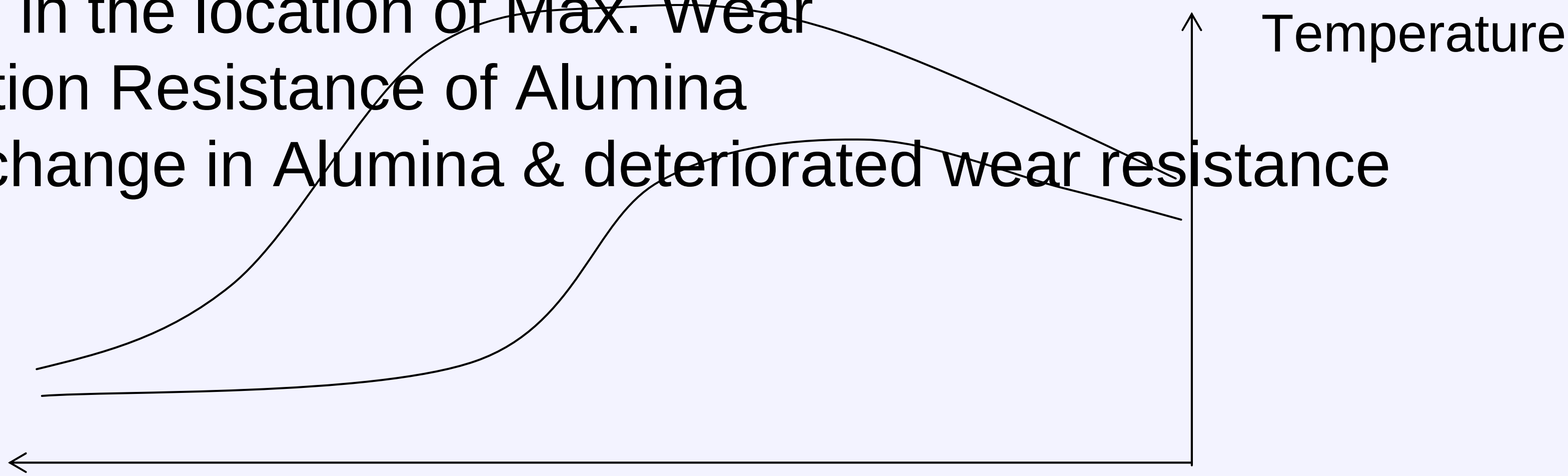


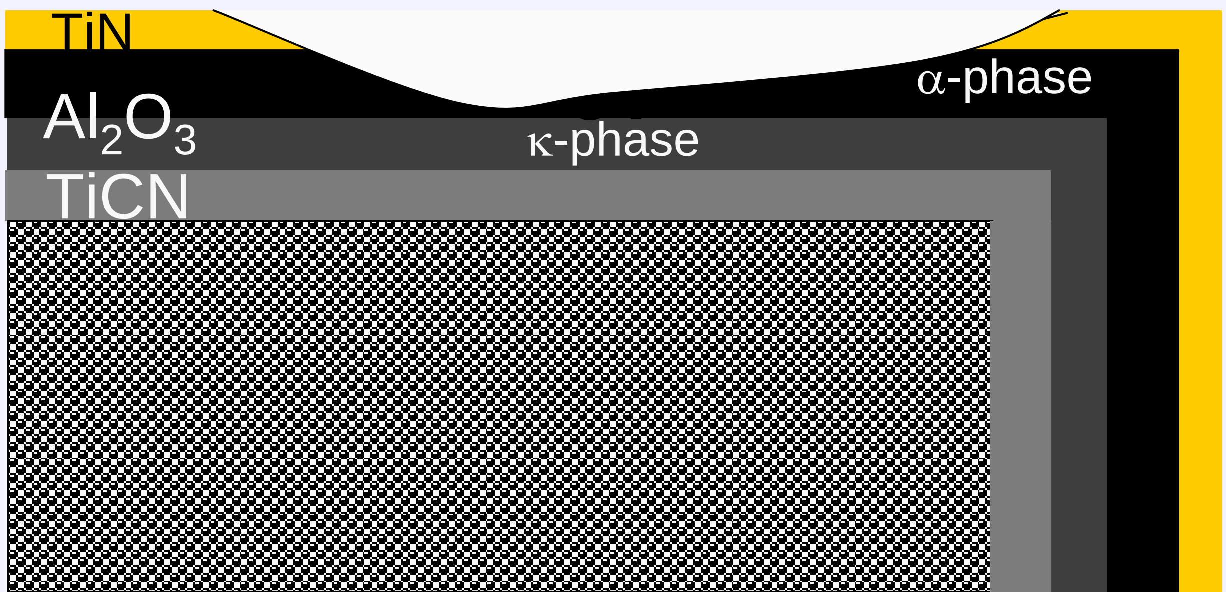
Crater wear evolution

Olortegui-Yume and Kwon, 2010

Interpretation of Results

Change in the location of Max. Wear
Dissolution Resistance of Alumina
Phase change in Alumina & deteriorated wear resistance



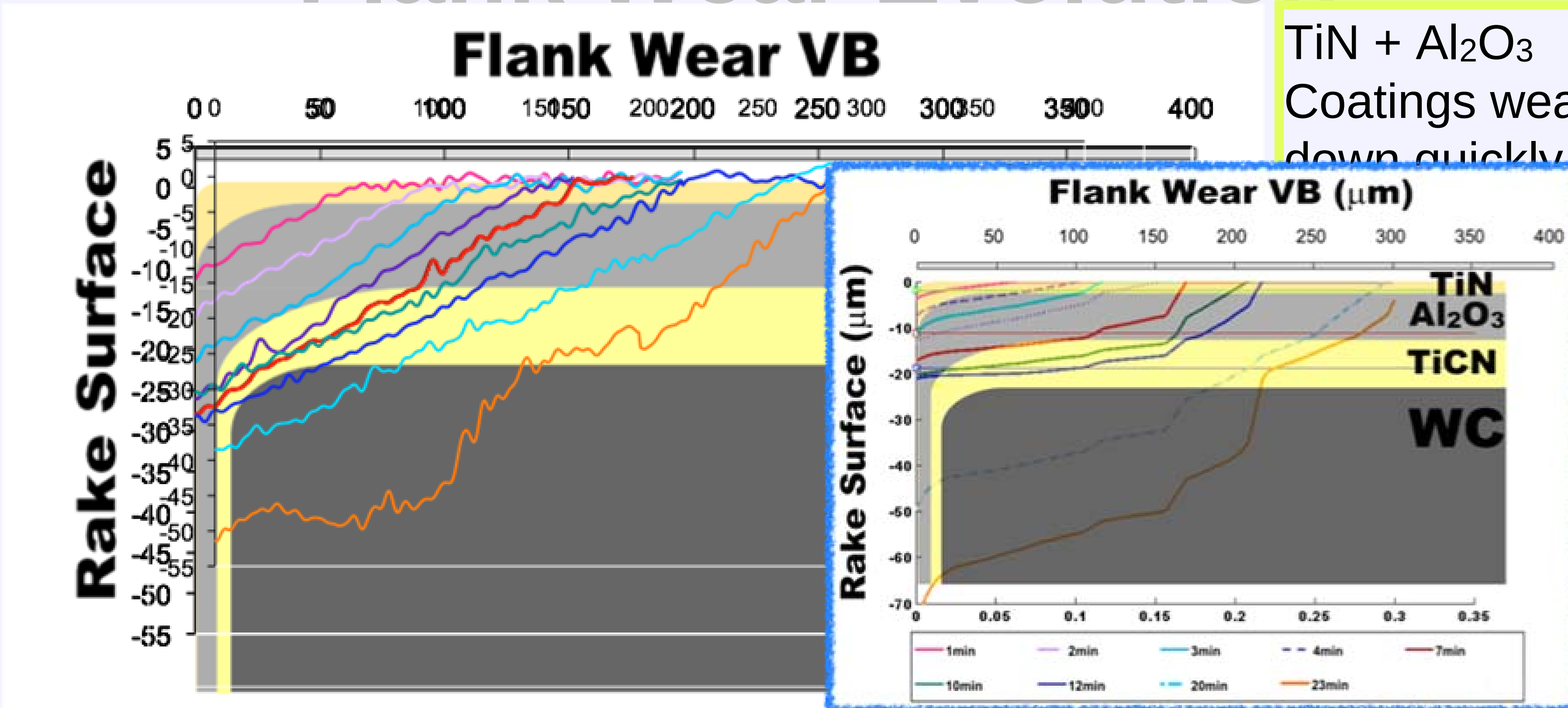


New Experimental Setup

- Turning of 1045 steels till carbide is exposed
- Four coatings on WC-6%Co substrates:
  - Boron Aluminum Magnesium ($AlMgB_{14}$) and TiB_2 alloy (BAM) *
  - $AlTiN+Si_3N_4$ binder (C7 nano-composite) provided by UNIMERCO Inc., Saline, MI.
  - AlTiN *
  - TiN *
- Sandvik Flat Carbide Inserts (SCMW 432)
- Determining **Friction** for each coating

* Coating provided by Fraunhofer, Inc., Michigan State University

Flank Wear Evolution



TiN + Al_2O_3 Coatings wear down quickly

worn down at 20-23 min

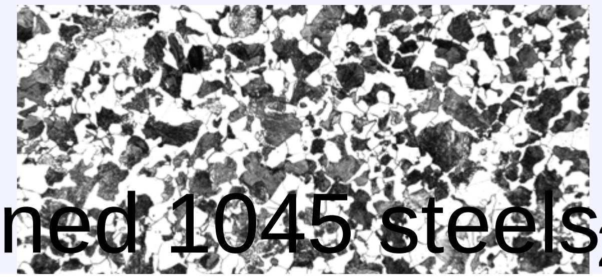
BATCH	TiN	Al_2O_3	TiCN
Ave. Coating Thickness	1.94μm	9.16μm	7.58μm

Hardness: Al_2O_3 < TiN < TiCN

1045 Normalized & Refined

Normalized & Grain Refined AISI1045

168 VHN



Refined 1045 steels

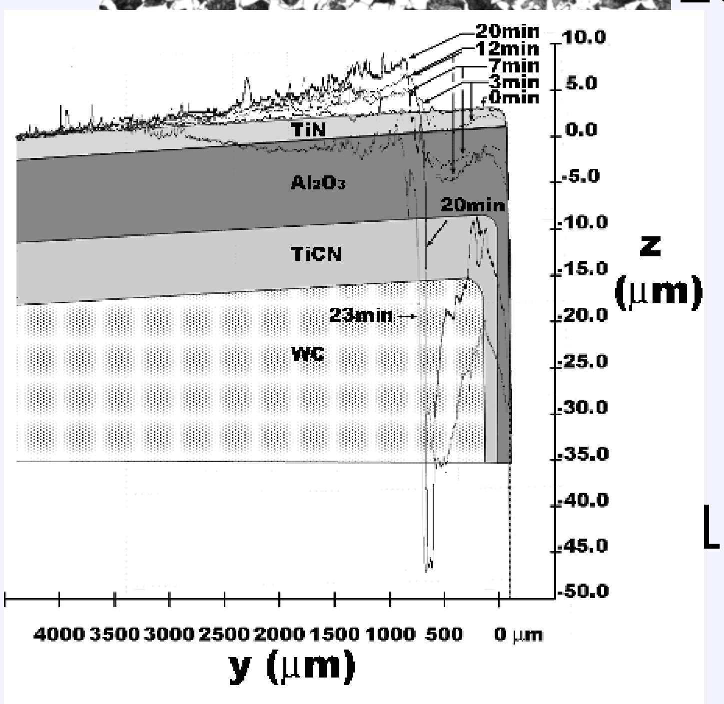
200x

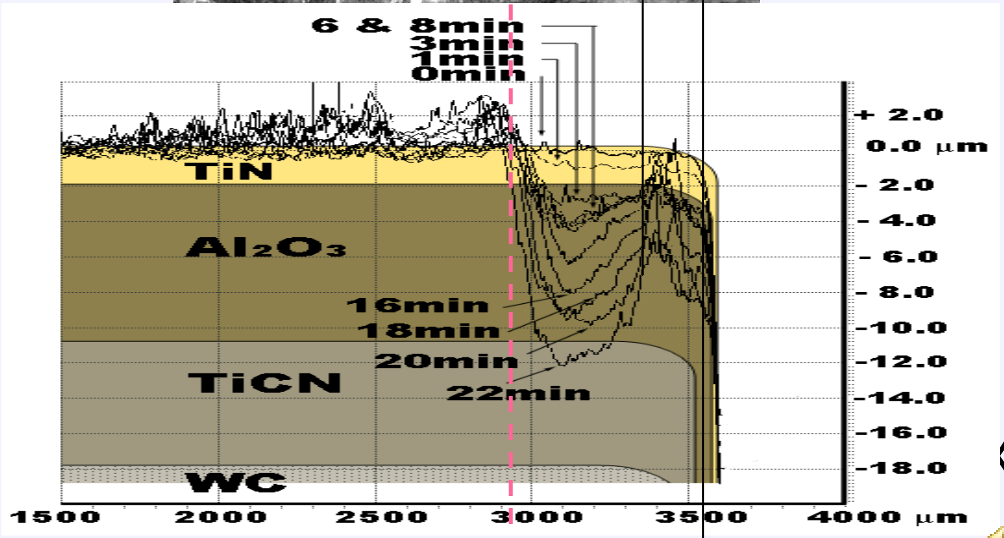
Normalized AISI1045

211 VHN

200x

Normalized 1045

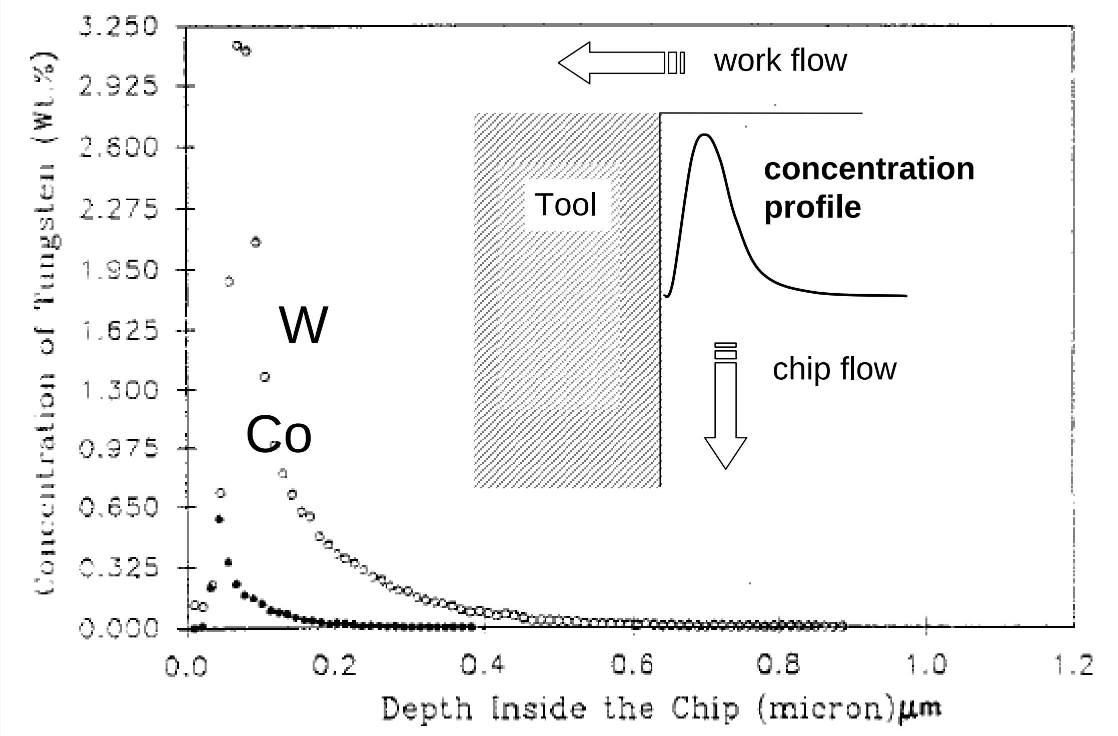




Verification of Tool Wear Mechanisms

Subramanian, Ingle, & Kay, *Surface and Coatings Technology*, **61**:293-299 (1993)

Secondary Ion Mass Spectroscopy



Carbide Tools with a Ferrous Material

Dissolution + Subsequent Diffusion

- Interactions within the chip's bulk

$$\frac{\partial X_i}{\partial t} = \boxed{\mathrm{div}\left(D_i\,\mathrm{grad}X_i\right)} - \boxed{\mathrm{grad}X_i \cdot \mathbf{v}^*} - \boxed{\frac{F_s}{c}}$$

$$\frac{\partial X_V}{\partial t} = \boxed{\mathrm{div}\left(D_V\,\mathrm{grad}X_V\right)} - \boxed{\mathrm{grad}X_V \cdot \mathbf{v}^*} - \boxed{\frac{F_s}{c}} + \boxed{\frac{F_{V,psz}}{c}}$$

$$\frac{\partial X_s}{\partial t} = -\boxed{\mathrm{grad}X_s \cdot \mathbf{v}^*} + \boxed{\frac{F_s}{c}}$$

where $$\boxed{\frac{F_s}{c} = k_f\left(X_i X_V - \frac{X_{i,eq}X_{V,eq}}{X_{s,eq}}X_s\right)}$$

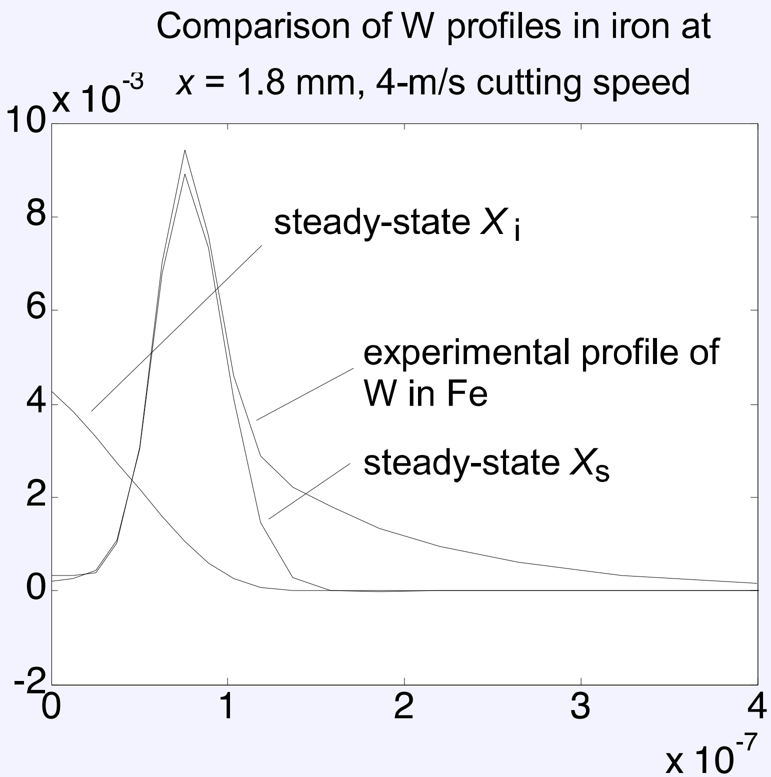
and $$\boxed{\frac{F_{V,psz}}{c} = k_V\left(X_{V,eq} - X_V\right)}$$

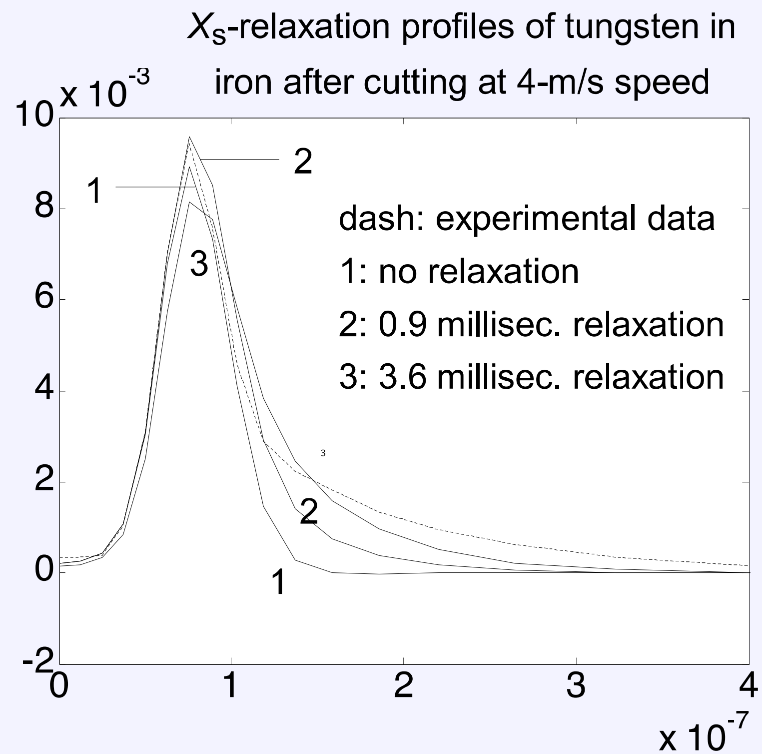
Frank-Turnbull Mechanism

$X_{(i,V,s)}$ are the mole fractions of interstitials, vacancies, and substitutionals

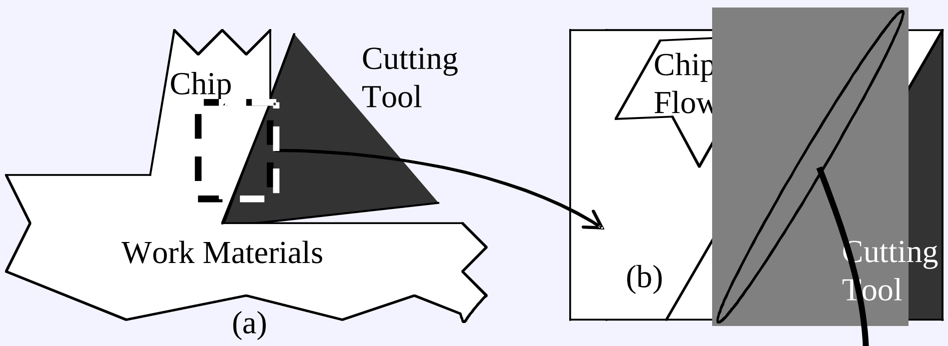
F_s/c : the rate of production of substitutional impurities via the Frank-Turnbull reaction

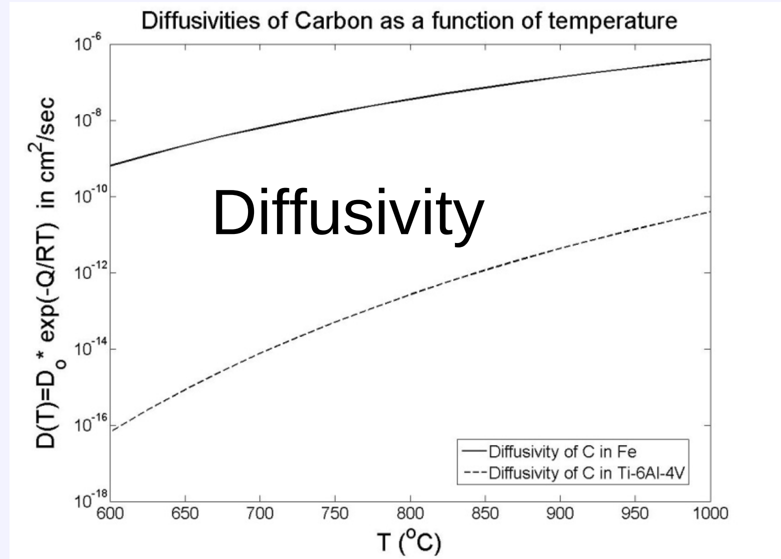
Sectioned View, Steady State



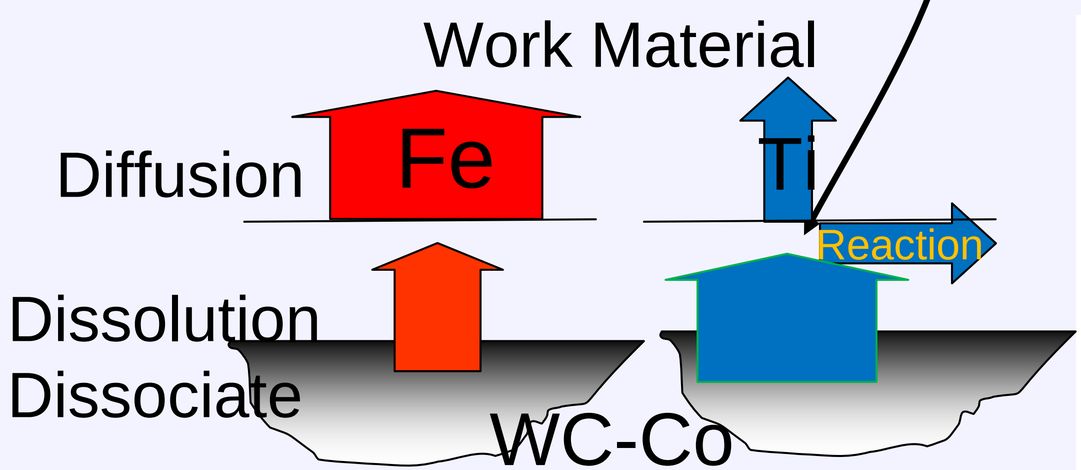


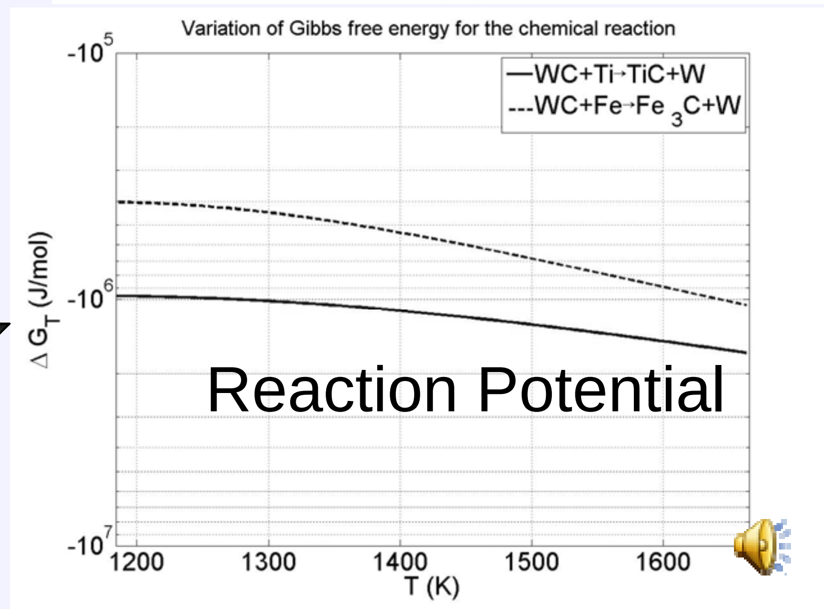
Difference in Wear Mechanisms





Traffic Jam Analogy





Dissolution controls in cutting steels
Diffusion controls in cutting titanium

Center for Advanced Cutting Tool Technology
Industry/University Coorperative Research Center.

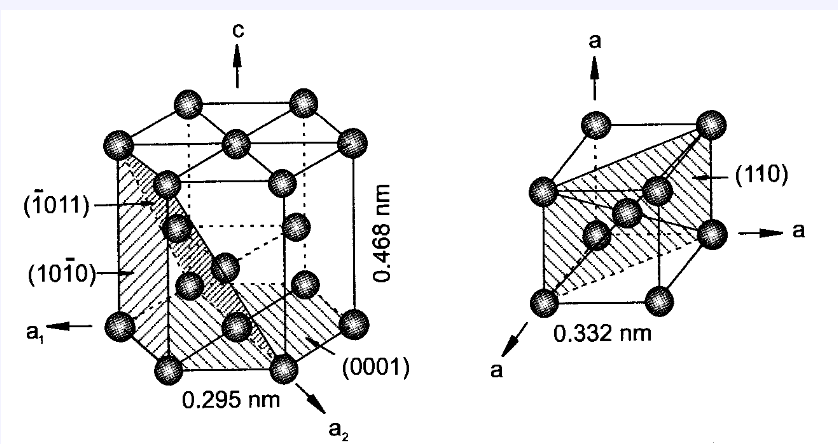
Tool Wear During Turning of Ti-6Al-4V using PCD and Carbide Cutting Tools

ARMY - ARDEC

David Schrock and Patrick Kwon
Center for Advanced Cutting Tool Technology
Michigan State University

Ti-6Al-4V

- Two phase metal
  - HCP (α- phase)
  - BCC (β-phase)
- Useful for Aerospace applications demanding high temperature strength to weight ratio and corrosion resistance

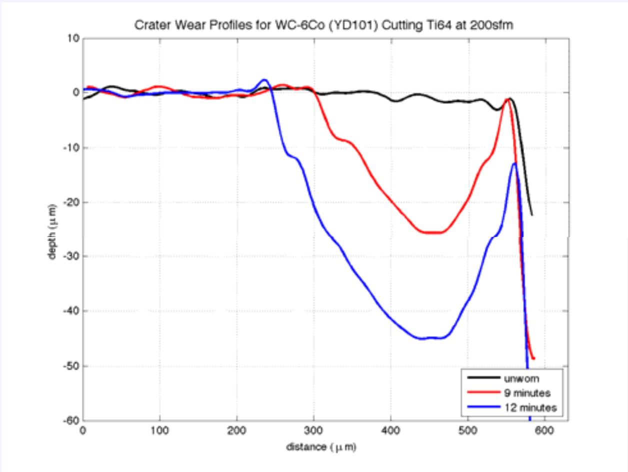


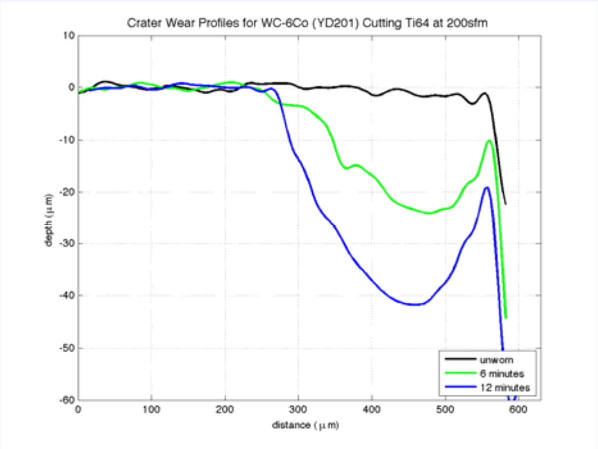
- Difficult to machine material
  - Low thermal conductivity
  - High reactivity
  - High strength at high temperature
  - Adhesion
- Current recommendations
  - Low cutting speed (<61m/min)
  - Flood cooling
  - Straight carbide cutting tools

Experimental Procedure

- Ti-6Al-4V work material turned on a YAMA SEIKI GA-30 lathe
- Cutting Tools
  - 2 grades of Carbide CNMA-432
    - YD101 (1um ave. grain size)
    - YD201 (2um ave. grain size)
  - PCD (Compax 1200P from Diamond Innovation) CNMA-432
    - with average grain size of 1.5 μ m with 92% volume.
    - 0 degree and 10 degree rake faces used
- Cutting Conditions
  - 3 Cutting speeds (61m/min, 92m/min, 121m/min)
  - Feed - .025mm/rev

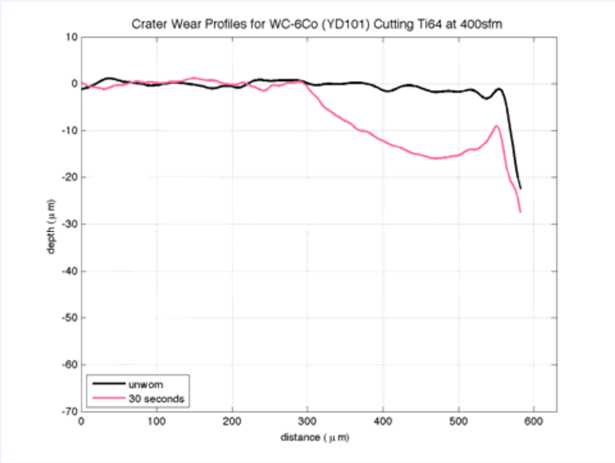
Crater Wear Profiles

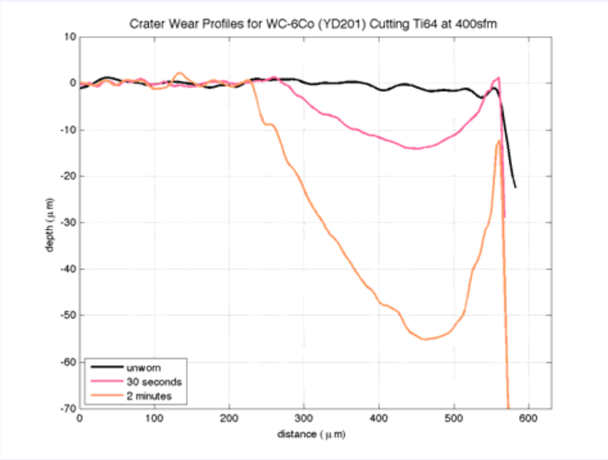




200sfm

400sfm



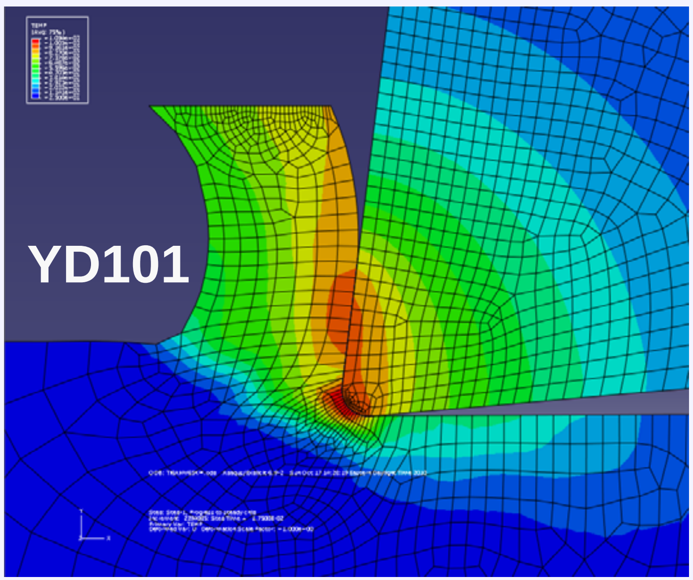


YD101 **YD201**

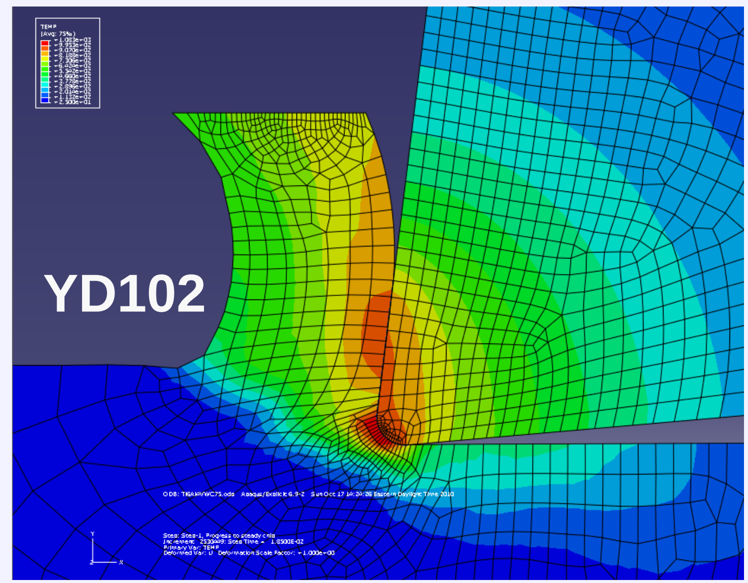
Slightly more crater wear on YD101 (smaller grains)

FE Simulation at *v*= 200ft/min

Work Material - Johnson-Cook model in literature
Tool Material - Thermally non-rigid but mechanically rigid



κ = 65kW/m (T_{max}=1095° C)



κ=75kW/m (T_{max}=1085° C)

The difference in the thermal conductivity (κ).
At 200sfm, the temperature difference of 10° .
At 400sfm, the difference of 15° .

Evidence of Phase-Dependent Tool Wear

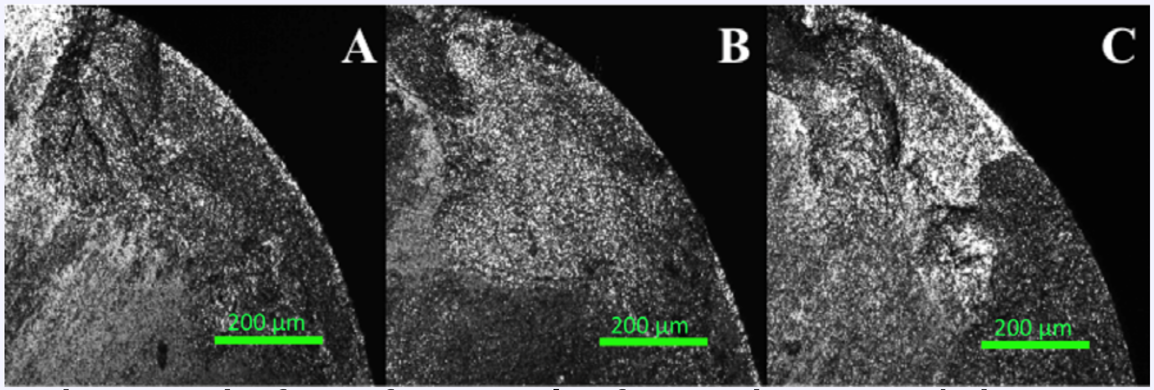


Figure: Rake face of PCD tools after cutting at 61m/min. Note the rough, scalloped surface

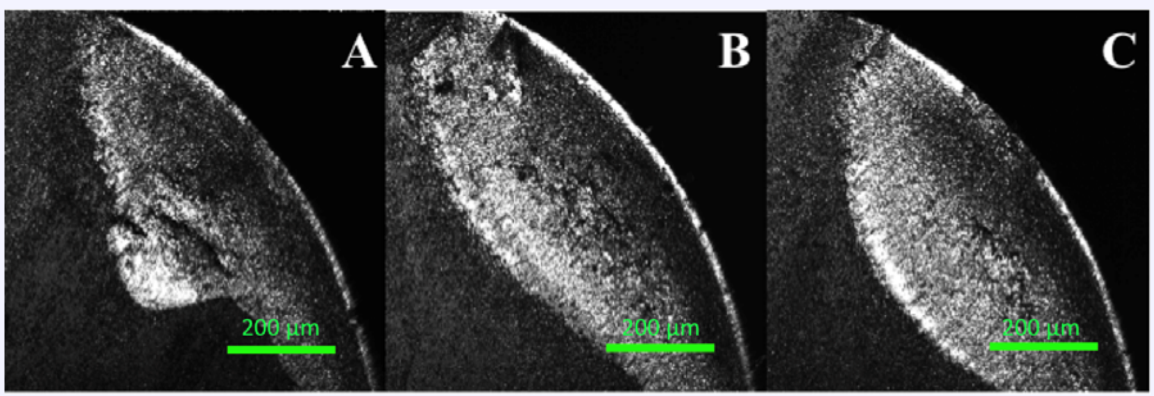
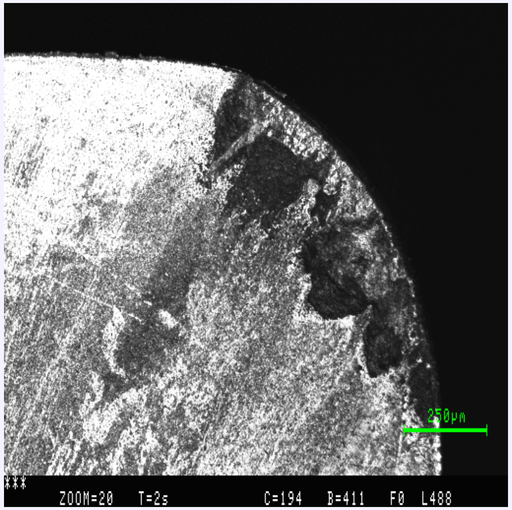


Figure: Rake face of PCD tools after cutting at 121m/min. Note the smooth craters

PCD versus Carbide Tool Wear

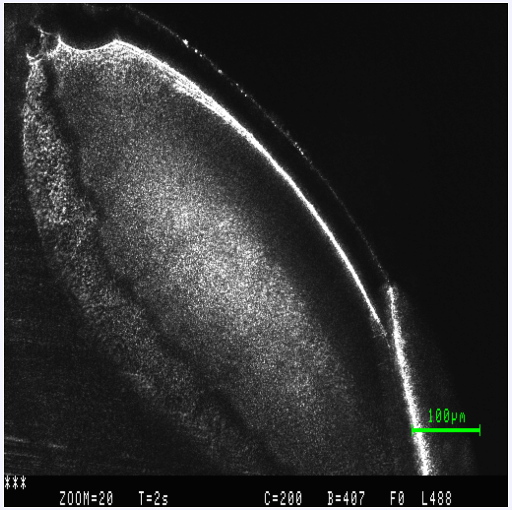
PCD

- Phase change dependent tool wear previously discussed explains differences between wear at high and low cutting speeds



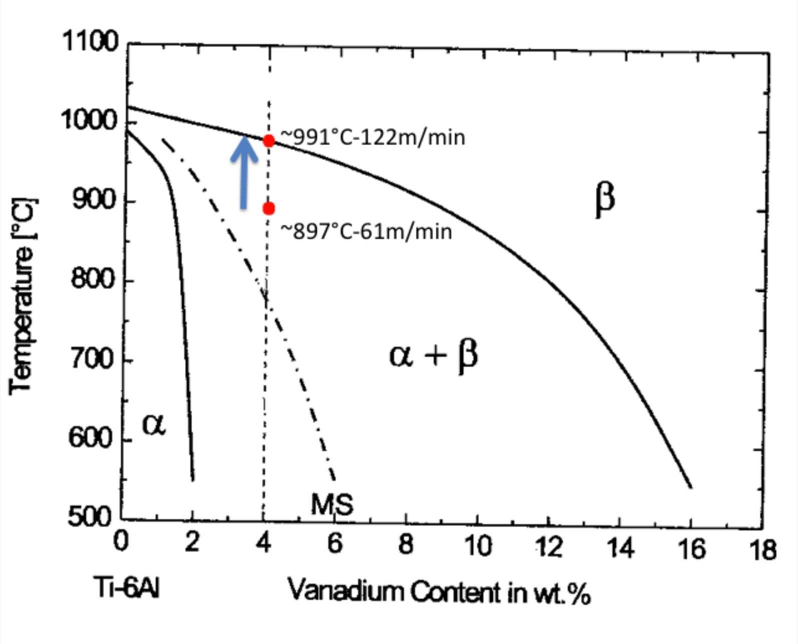
Carbide

- FEM on the carbide tools predicts cutting temperature over 1000C for the carbide tools at 61m/min
  - Characteristic smooth craters for all cutting speeds



Temperature from FEM

- FEM show temperatures for machining with PCD at 61m/min of 897C
  - From phase diagram, mostly alpha phase
- At high cutting speed, temperature approaches 1000C
  - Transformation to beta phase



Phase diagram for Ti-6Al-V system

Table 1: Temperature Estimation from FE Simulation

Cutting speed	PCD tools	WC-6Co tools
61m/min	897°C	1095°C
91m/min	942°C	1156°C
122m/min	991°C	1198°C

Impact on Tool Wear

Low Cutting Speed

- Chip is mainly α-phase (HCP) or $\alpha + \beta$ phase
  - Less favorable plastic deformation properties
    - Relative sliding at the tool work interface
    - Periodic separation of adhered material by fracture of tool, creating scalloped wear pattern
  - Much less self diffusivity
    - Fewer vacancies, slow dissolution wear

High Cutting Speed

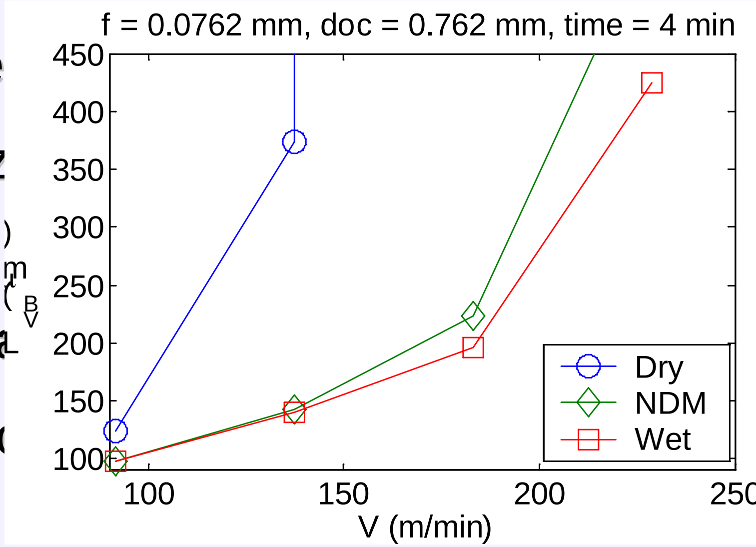
- Chip has transformed to β phase (BCC)
  - **Self-diffusivity 5 orders of magnitude higher for β at 1000C than for alpha at 500C**
    - Promotes generation vacancy dislocations which can accept interstitial carbon atoms (dissolution wear)
  - Improved plastic deformability
    - allows chip seizure, increasing dissolution wear
    - Separation of work material from tool occurs inside of chip
      - Prevents scalloped wear pattern

Ongoing/Future Work

- SEM and optical microscopy to compare phases present in deformed chip to that of the unreformed work material
- Development of 3-d FEM simulation to more accurately predict temperature within tool material during cutting
- Determine investigate the kinetics of the phase change

Minimum Quantity Lubrication

- MQL Parameters which significantly influence on the effectiveness of MQL machining
  - Droplet size: oil mist size & health issue
  - Droplet distribution: wetting area & nozz distance
  - Other parameters: Air pressure & flow ra
  - Wetting angle: lubrication performance (coatings (?)
  - Improvement of MQL lubricants



x-GNP modified MQL oil

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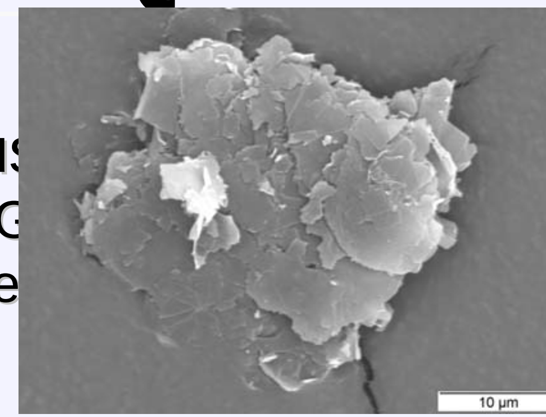

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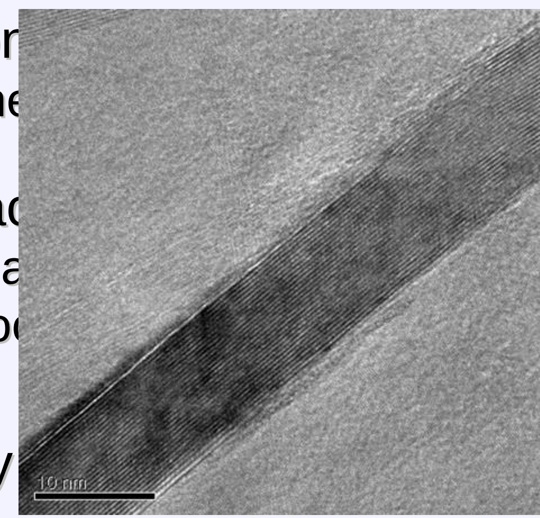
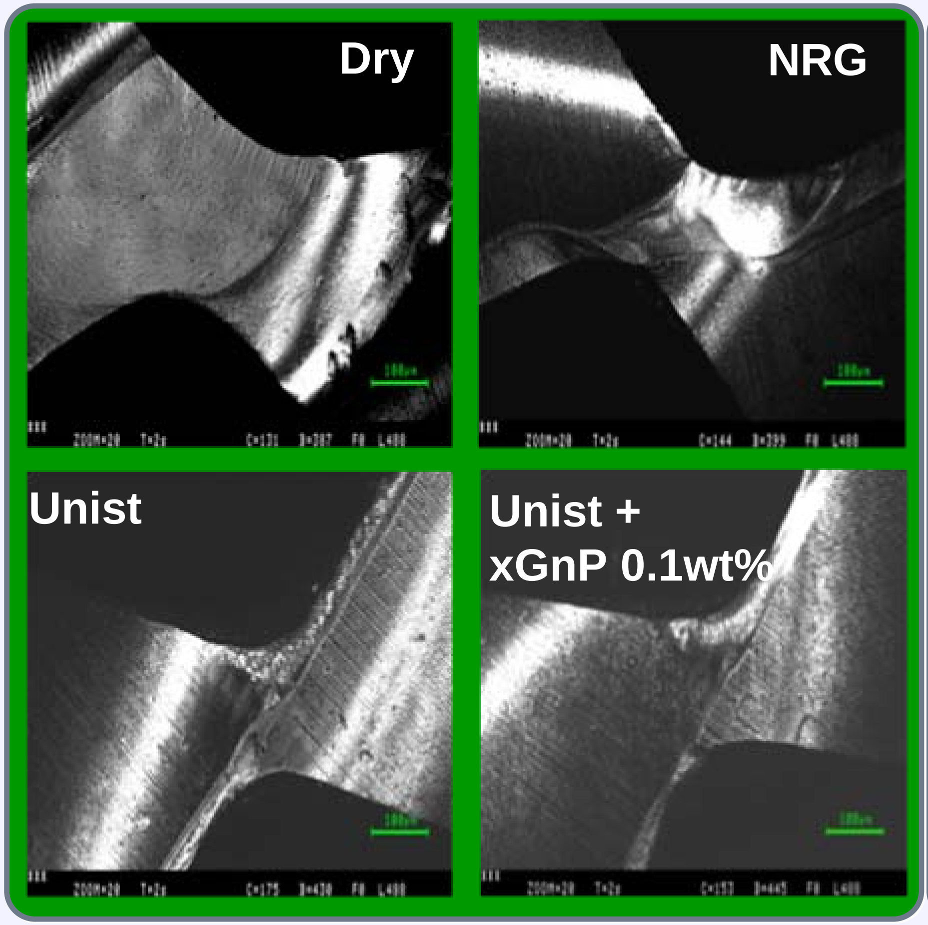
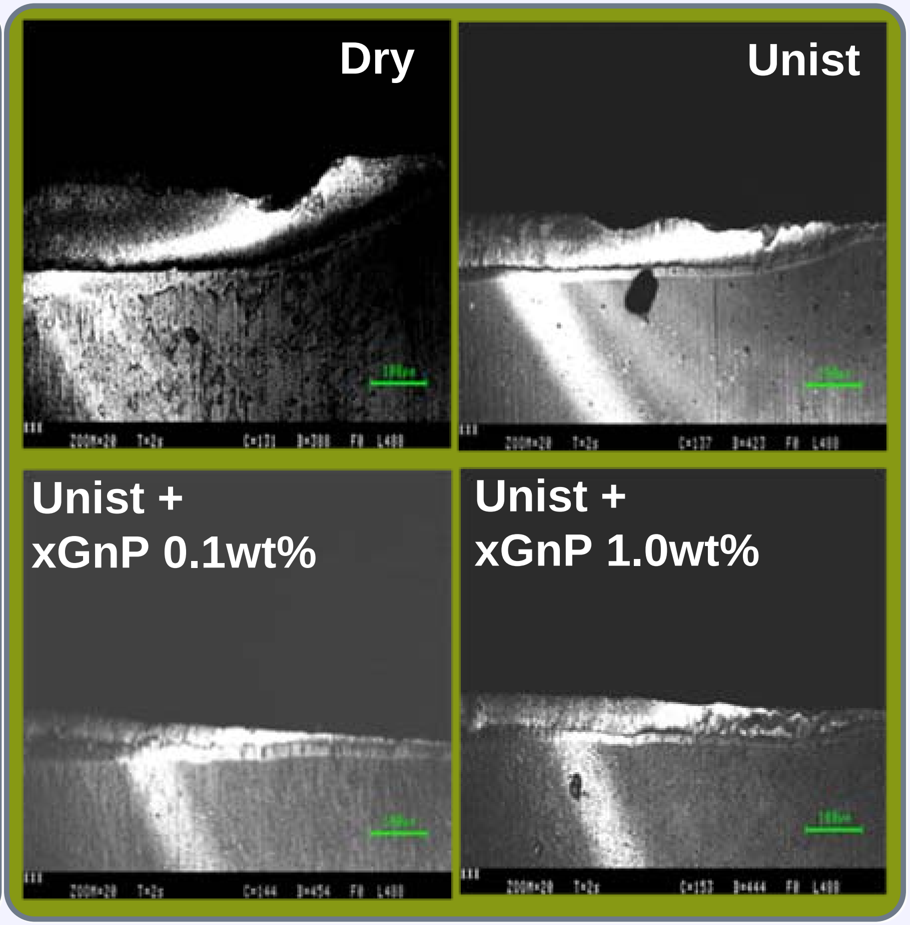


Comparative Test

Central wear (8th layer) at 3500 RPM



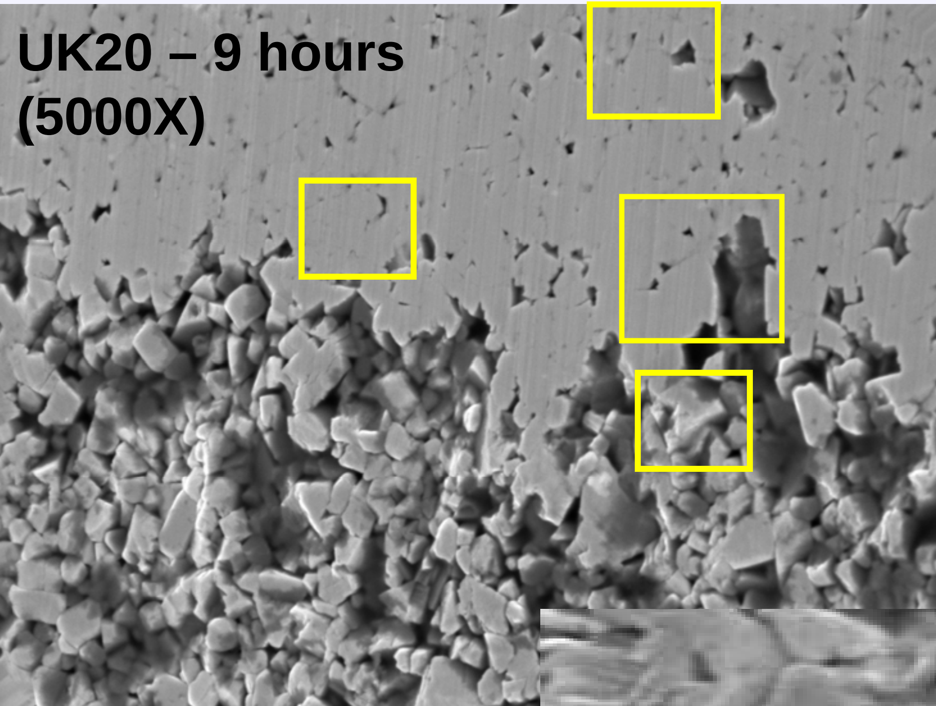
Flank wear (8th layer) at 4500 RPM

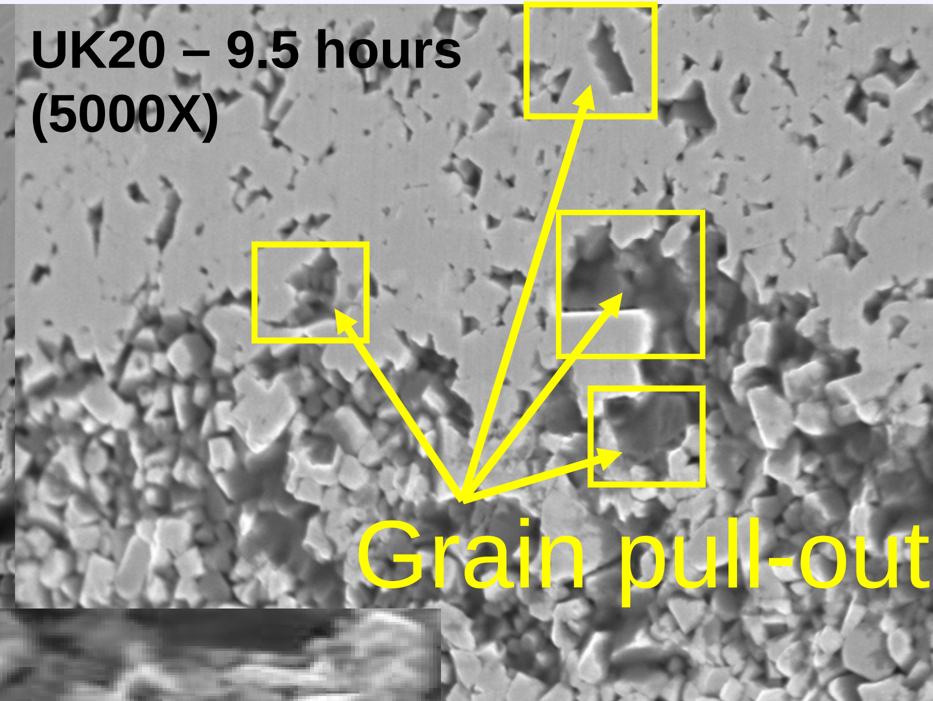


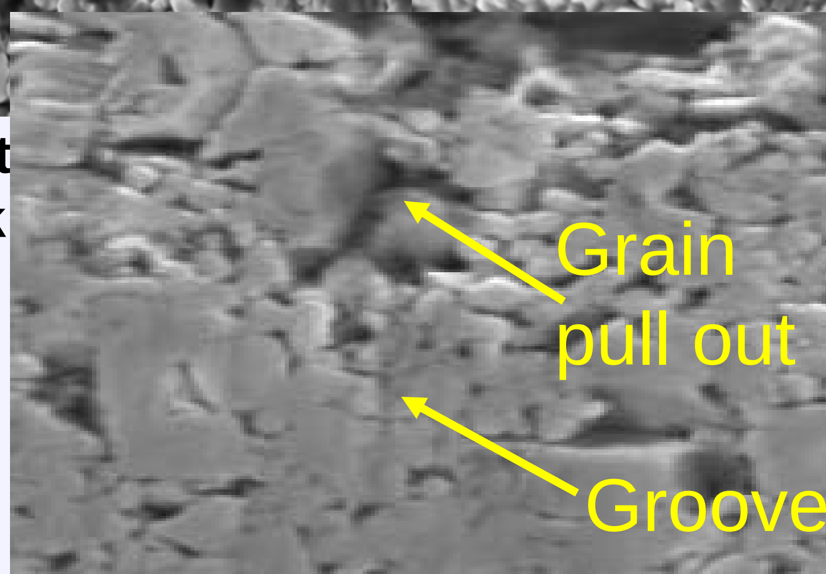
Machining Soft Materials: Commercially Pure Aluminum

Xin Wang and P. Kwon
Department of Mechanical Engineering
Michigan State University
East Lansing, MI

Evidence of Carbide Grain Pull-out

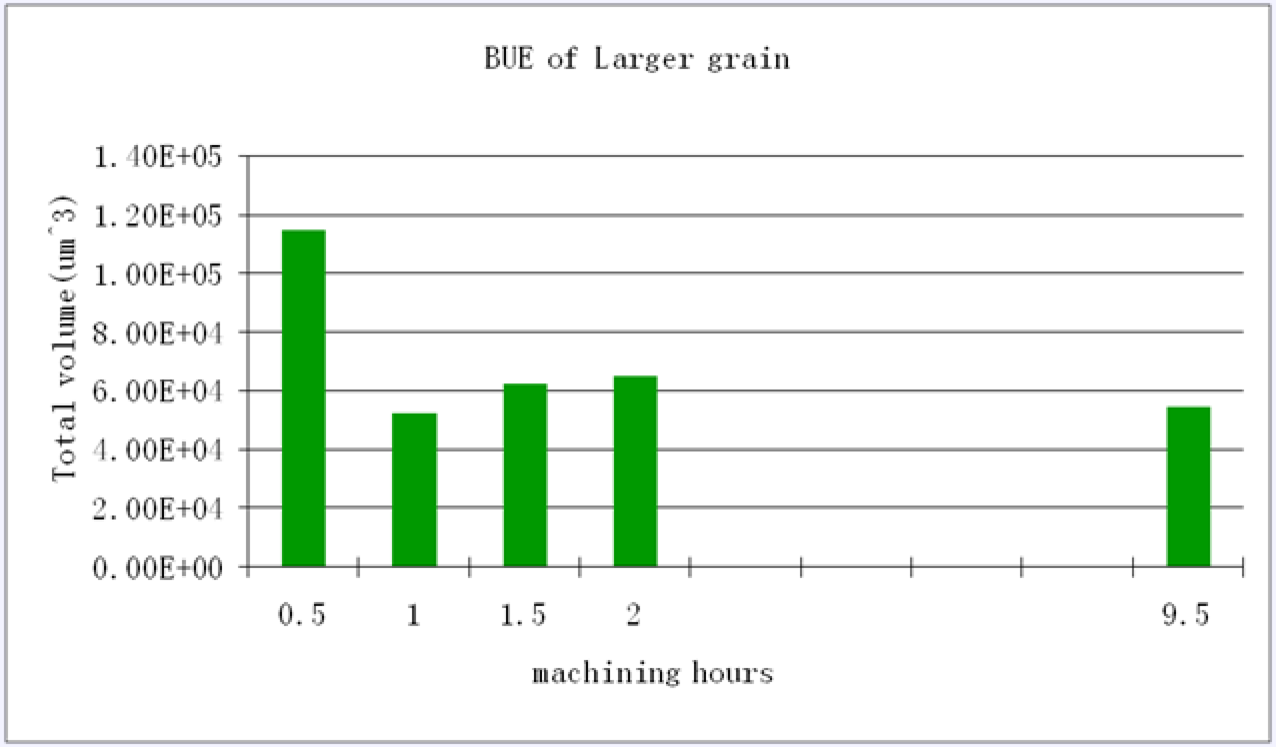






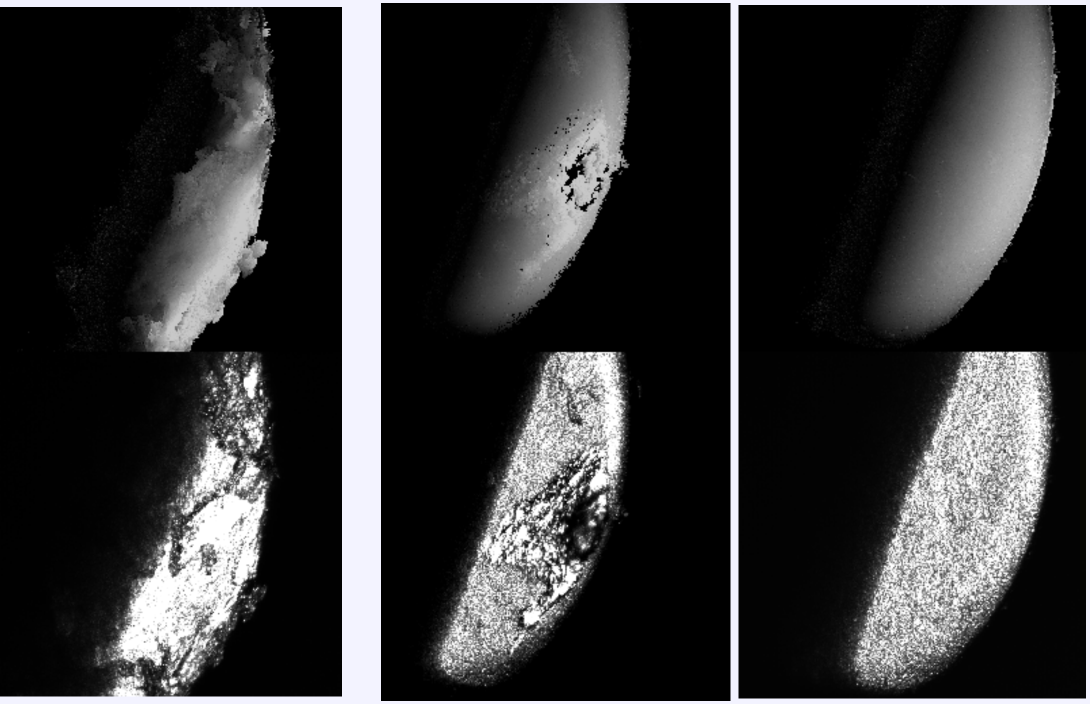
Grain pull-out aft ... g at same location on flank

BUE evolution



Evolution of volume of built up edge.

2 types of BUE



Before etching etching for 2 hour & for 10 hours with 1% NaOH

Element (at %)	Initial BUE	Thin layer
Al	77.65	68.48
C	19.54	21.92
O	2.63	9.41
Si	0.18	0.19
W	0	0

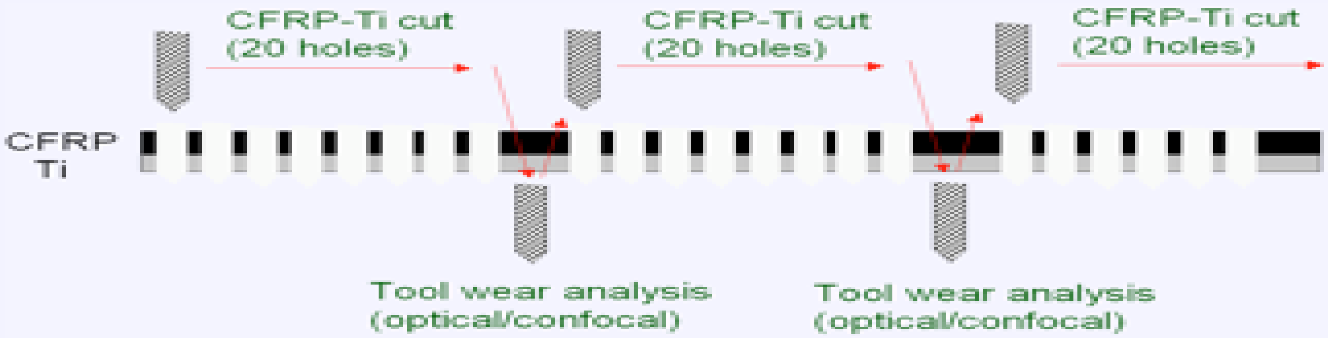
- Carbon comes from the carbon contamination in SEM measurement.
- High concentration of oxygen was detected in the thin layer [6,7]. It indicates metal oxide exist in thin layer.

Drilling CFRP/Ti Stack

K. Park & X. Wang
Department of Mechanical Engineering

Drilling Composite/Metal Stacks

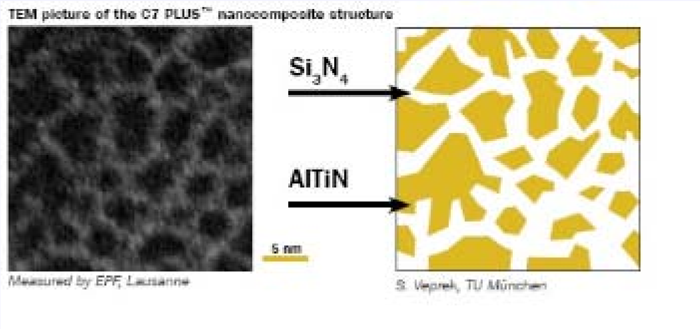
- **Drilling Experiments at WSU**
  - CNC (HAAS Mini-Mill)
  - **Carbide, PCD & BAM**
  - Mist machining
- **Post Analysis ay MSU & WSU**
  - **Flank/Outer edge/Crater wear after every 20 holes (SEM, confocal microscope)**



Cutting tools (3 types)	WC (10% Co micro-grain)	BAM coating (WC) (10% Co micro-grain)	PCD (Bimodal grade)
Cutting speed	CFRP 2000 rpm; Ti 400 rpm (WC) - 300 rpm (PCD)		
Constant parameters:	Drilling feed: 0.0762 mm/rev (CFRP) and 0.0508 mm/rev (Ti) Coolant: Water-soluble cutting fluid, Mist coolant flow rate at 16 mL/min.		

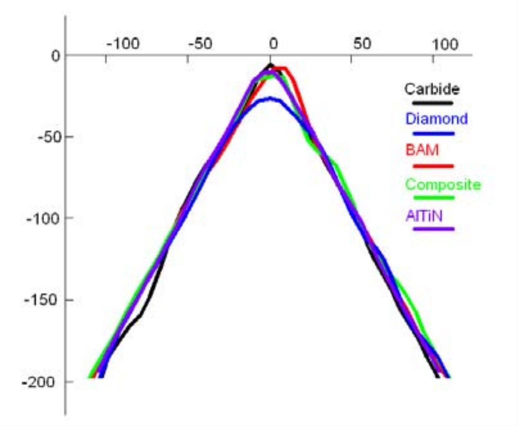
Tool coatings

1. CVD Diamond coating – Boeing
2. BAM coating – Fraunhofer
3. Nanocomposite coating – Unimerco's C7 Plus



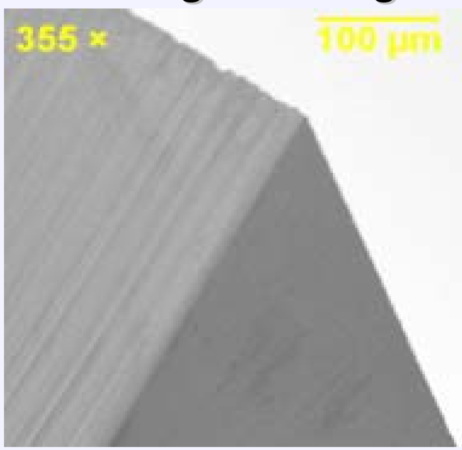
4. AlTiN coating – Unimerco (from Europe)

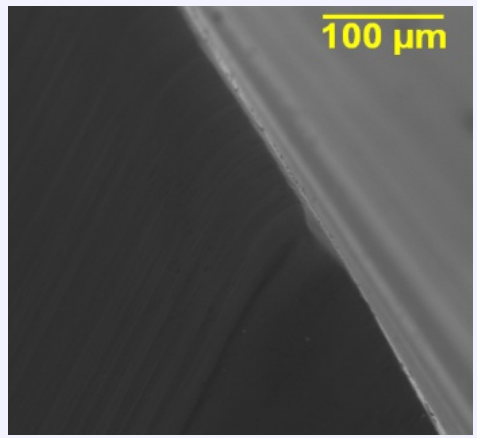
Coating	Cutting edge angle (º)	Coating thickness
Uncoated	59.2	/
BAM	58.7	3.5 µm
Diamond	61.2	12.5µm
Composite	57.0	3 µm
AlTiN	60.2	3µm

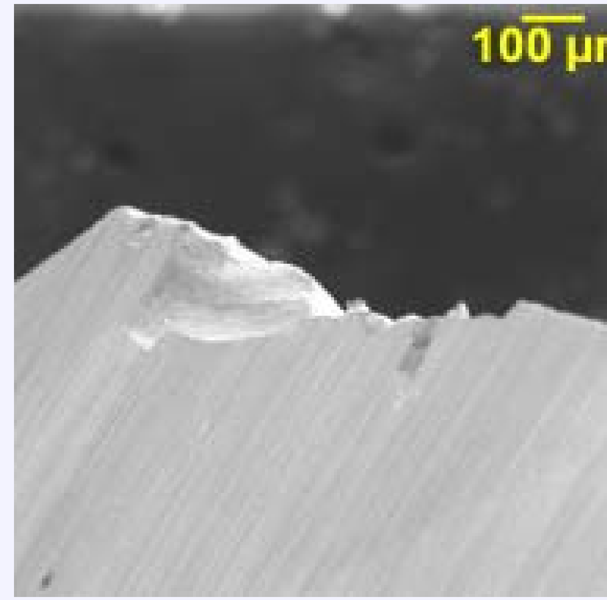


Observation

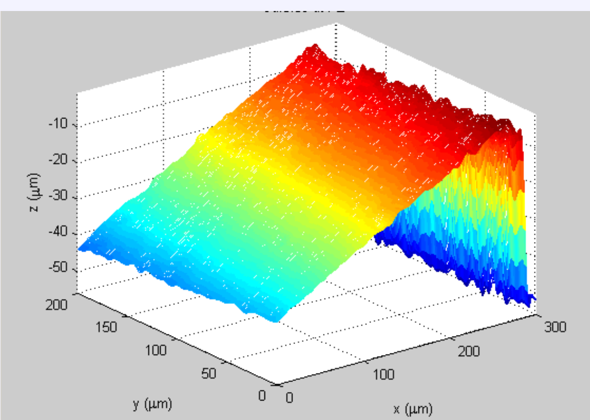
- Tool wear in CFRP drilling was blunting the edge.



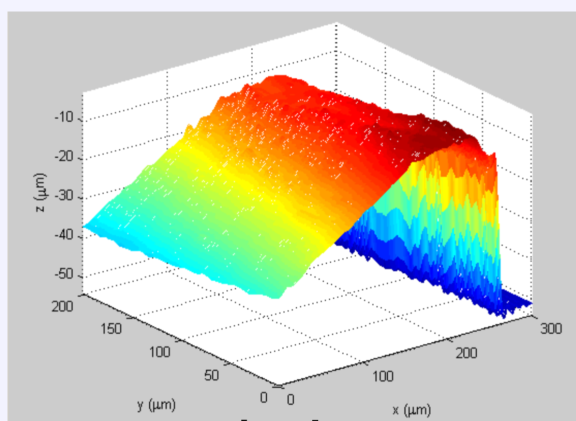




- Tool wear in TI drilling was Chipping.



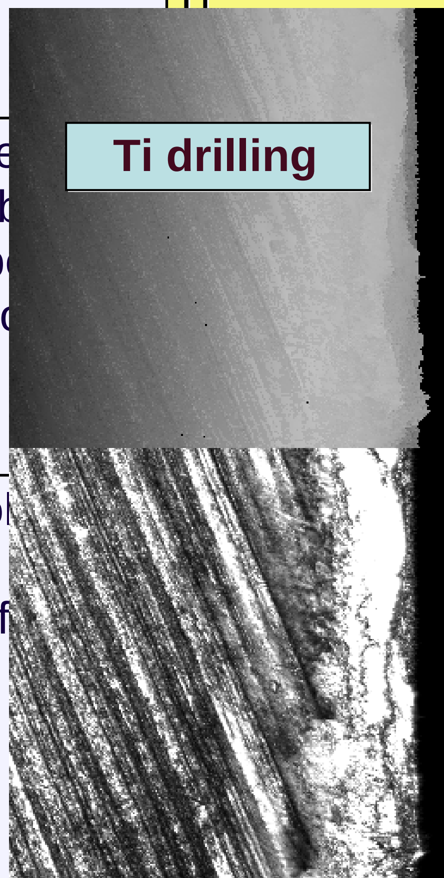
New

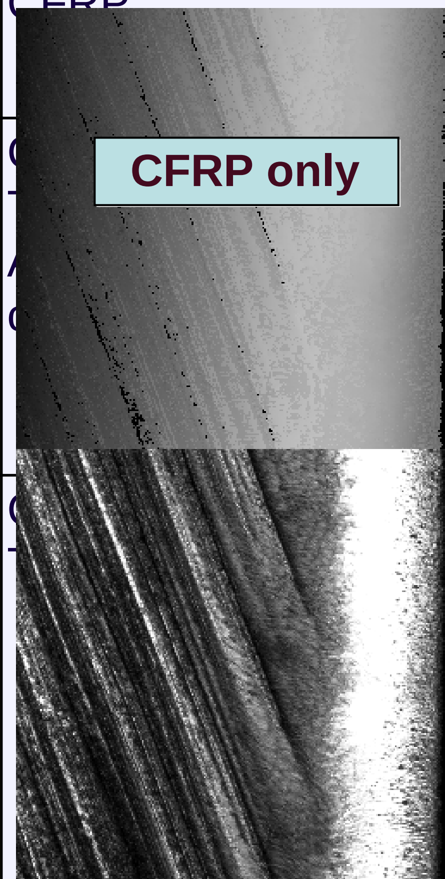


20 holes

Wear Mechanism - Stack

	CFRP	Ti	CFRP	Ti
Carbide	Abrasive we to carbon fib through 2-bo abrasion pro	hesion s built- d	C T A c	Ti adhesion → WC grains pulled out as built- up-Ti removed
PCD	Minimal tool due to high hardness of	on + g at es due of	C T	Ti adhesion + Major chipping areas get larger due to additional chipping





Edge blunting wear in CFRP drilling

- Our hypothesis is
  - In metal machining, stagnation zone protect the cutting edge. In CFRP machining, there is **no stagnation zone** to protect the cutting edge

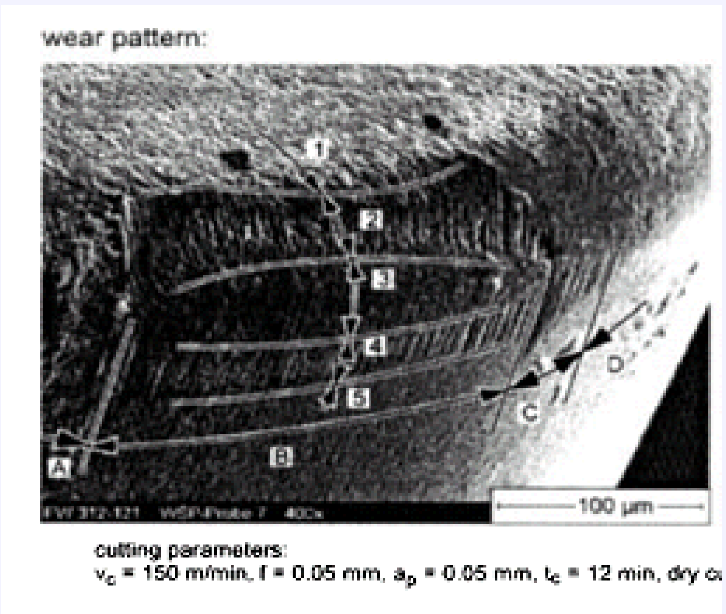


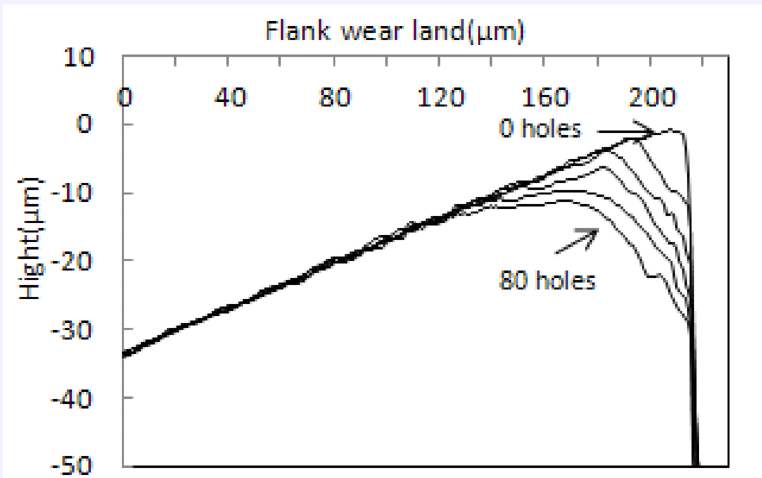
Figure 1. Wear pattern of a PCBN tool in hardened steel machining

Zone 2 (crater wear)
Zone 4 (flank wear)
Zone 3 (cutting edge – no wear)

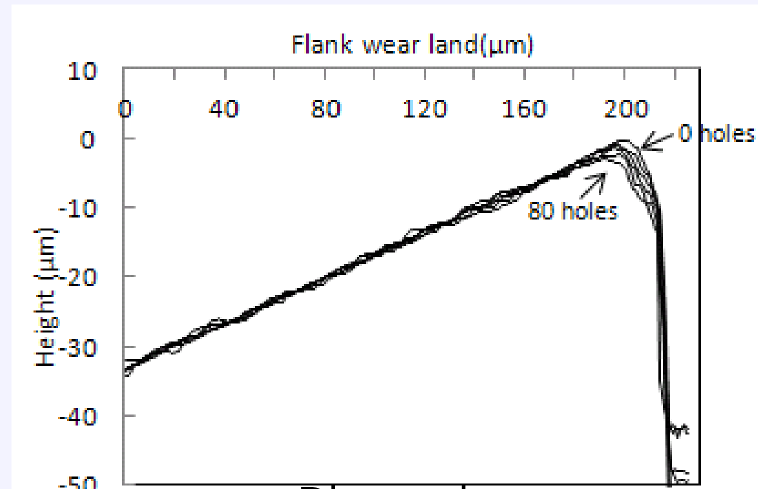
Cutting edge has no wear in metal machining.

Because there is no relative sliding or very slow sliding of work material on the cutting edge of the tool.

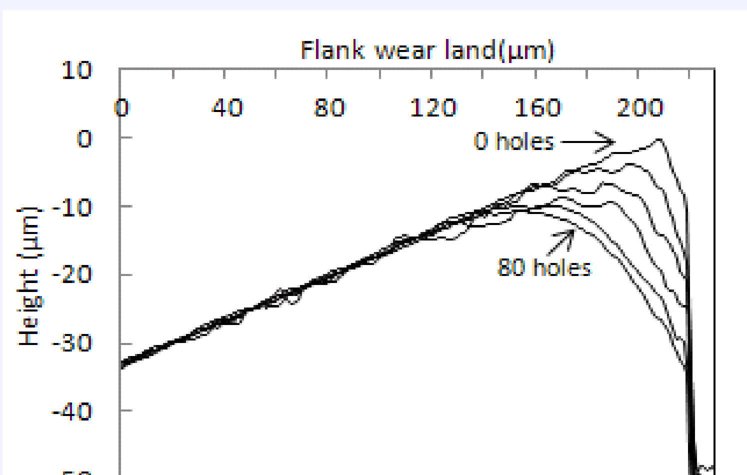
Wear of coated drills (CFRP)



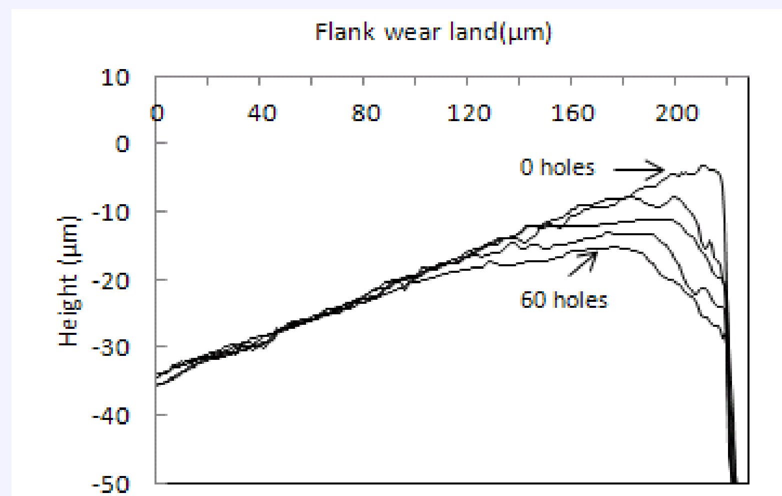
Uncoated carbide



Diamond



Nano-composite



AlTiN

Wear mechanism in CFRP drilling

- Abrasive wear or sliding wear?

Table 2. Abrasive wear rate and sliding wear rate of the coatings

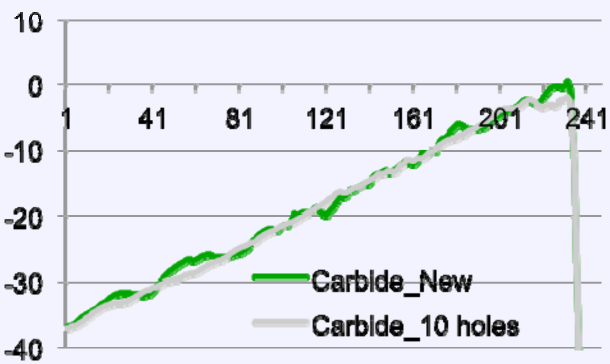
	Hardness at 25° C (GPa)	Relative abrasive wear rate	Sliding wear rate (mm3/Nm)	Relative sliding wear rate
Uncoated carbide	26	1	1.39E-07	1
Diamond	70	0.007	1.22E-08	0.088
BAM	43	0.078	7.27E-07	5.230
AlTiN	40	0.113	3.98E-07	2.863

Wear volume (um^2)	Total wear	Relative coatings wear rate
Uncoated	641	1
Diamond	71	0.111
BAM	1015	3.992
Composite	761	1.811
AlTiN	944	2.772

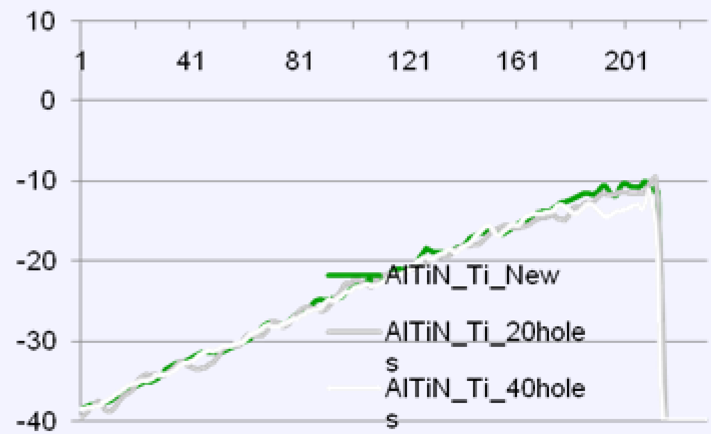
Abrasive wear rate of coating was predicted by the coating hardness data and abrasive wear equation.
Sliding wear rate was acquired by a tribo-meter test experiment.
(Sliding wear is too complicated, and could not be predicted by material property.)

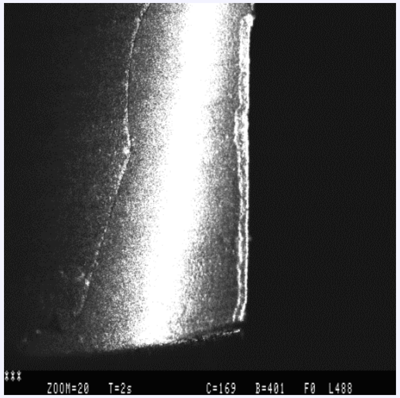
Tool wear in Ti drilling

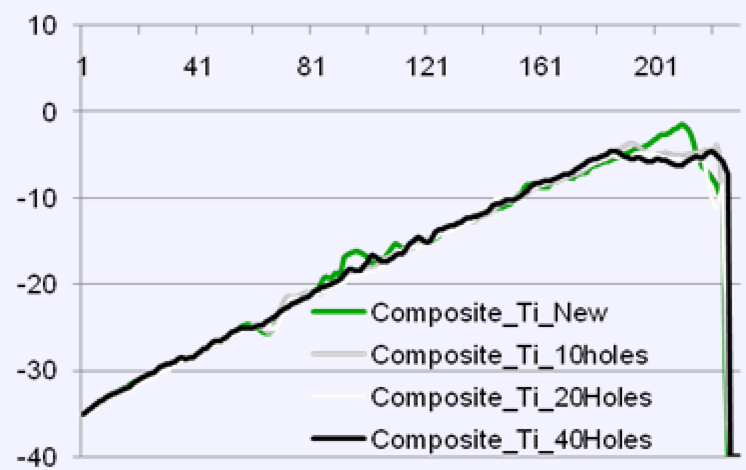
- Besides the edge chipping, the tool wear in Ti drilling is much smaller than in CFRP drilling.



Carbide: Edge chipping at 20 holes



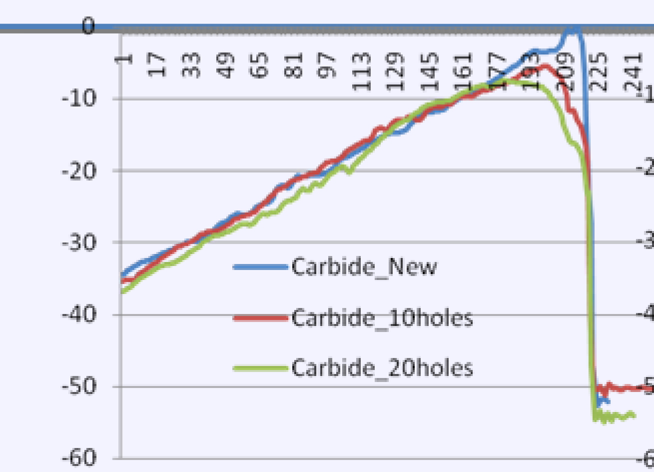




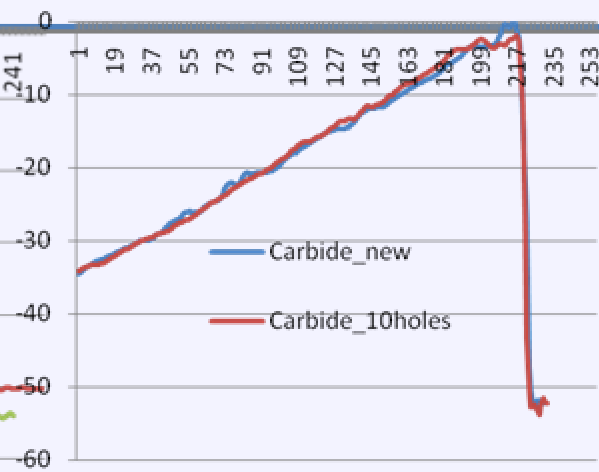
Diamond: Coating flake off at 10 holes

Uncoated Carbide Tools

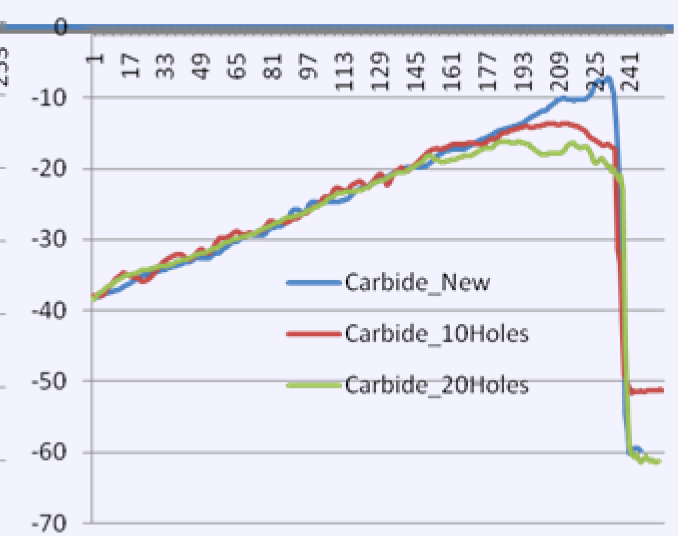
Wear on CFRP only +
Wear on Ti only =
Wear on Stack



CFRP only



Ti only

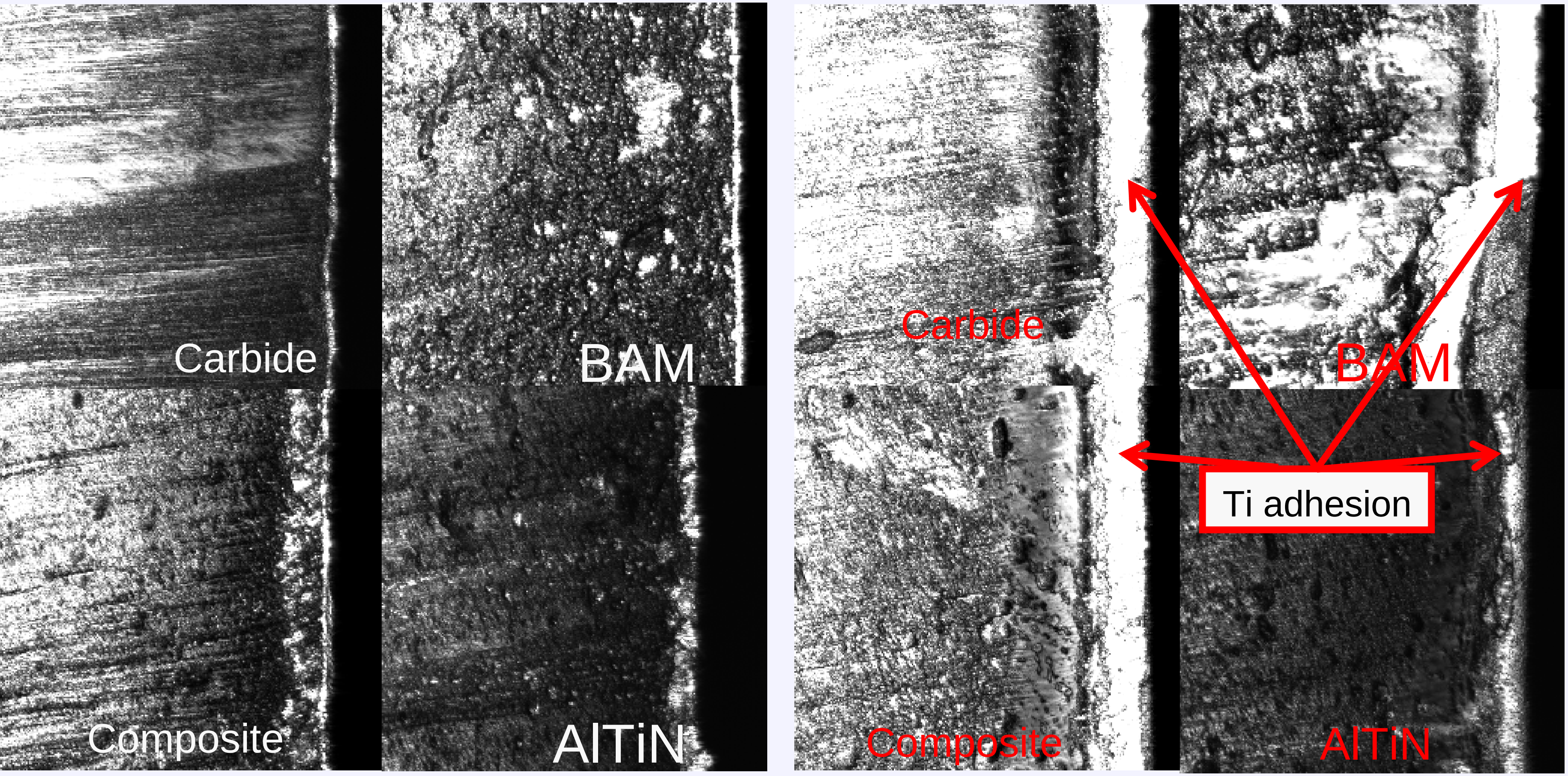


Stack

Comparison of Ti and Stack drilling

Ti drilling 20 holes

Stack drilling 20 holes



More titanium adhesion in stack drilling than Ti drilling.
It may due to the edge rounding in stack drilling
-> more stagnation material at the cutting edge

Conclusion

- The edge blunting (dulling, rounding) wear in CFRP machining is due to lack of a work material stagnation zone in front of the cutting edge, which would normally prevent the edge wear.

- The sliding wear rather than abrasive wear in CFRP machining.
  - Hard coating without good sliding wear resistance do not increase the tool life.

Acknowledgement

- NSF for supporting I/UCRC on Advanced Cutting Tool Technology
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- ARMY-ARDEC
- (New Tech Ceramics, Sandvik, Unimerco, GM & UNIST)