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Tool Wear Evolution in Titanium Machining

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3/29/2014

AGENDA

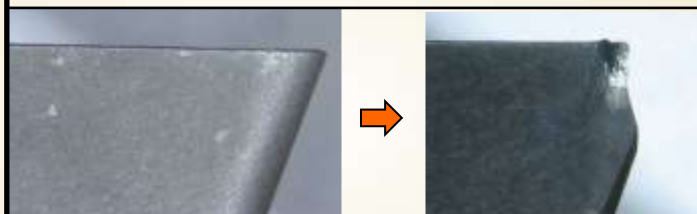
- **Introduction to Titanium machining**
- **Current knowledge/practices**
- **Special topics:**
    1. **VTW & M-Ratio**
    2. **Relationships with MRR**
    3. **Mapping Wear Mechanisms**
    4. **DOE-HPC Project**

A Few Minutes into Machining Ti-6Al-4V…

Solid carbide end mill [5-flute, 0.5" (Φ)]

Coated carbide milling insert (flank face)

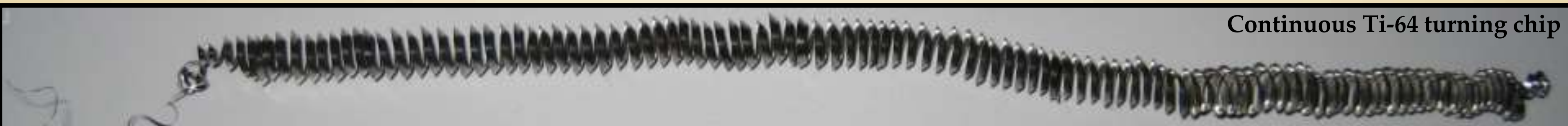
Uncoated carbide milling insert (flank face)



Climb milling on Ti-6Al-4V

Burnt chip

Even with frequent tool wear checks at conservative conditions ➡ Catastrophic tool failures!

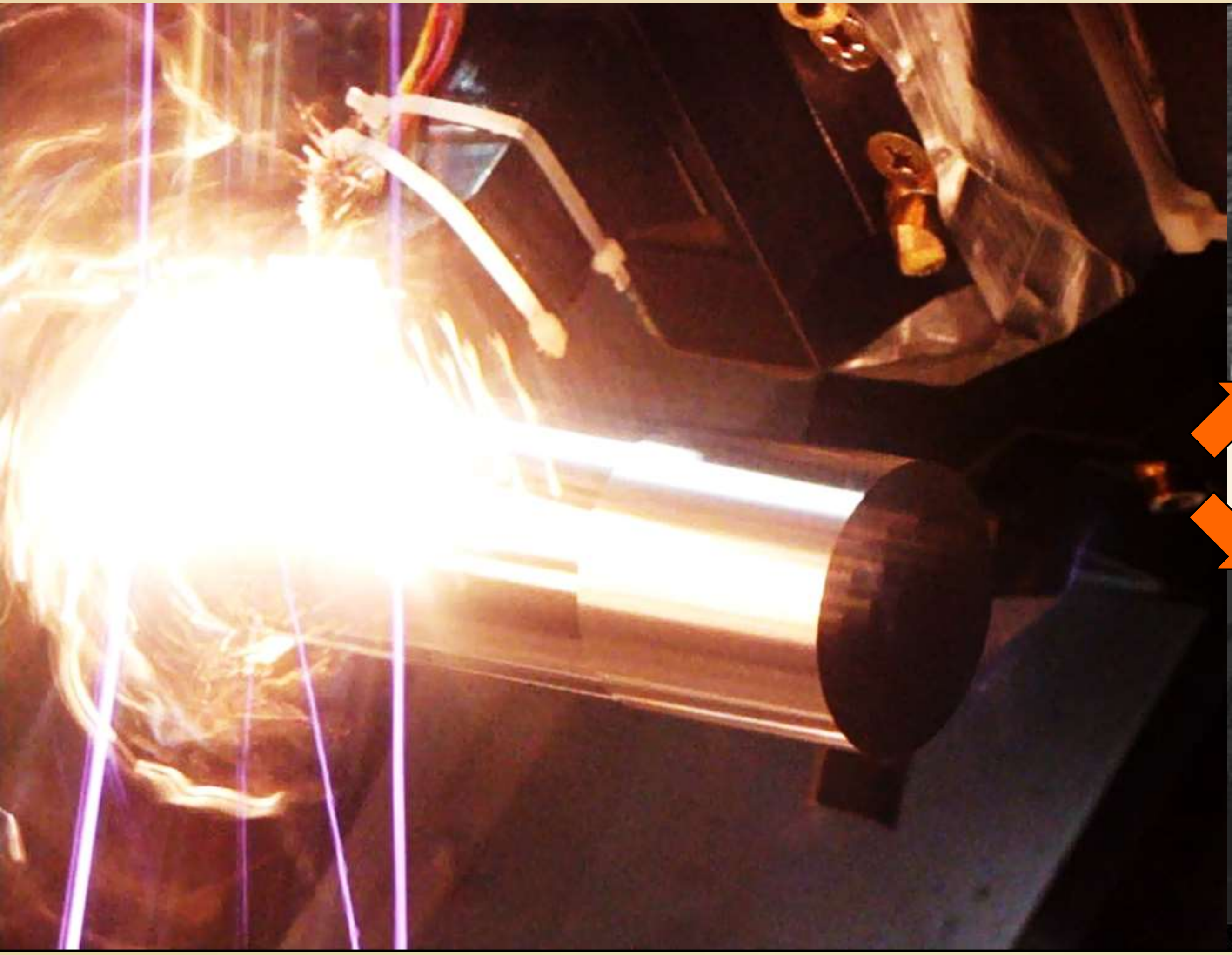


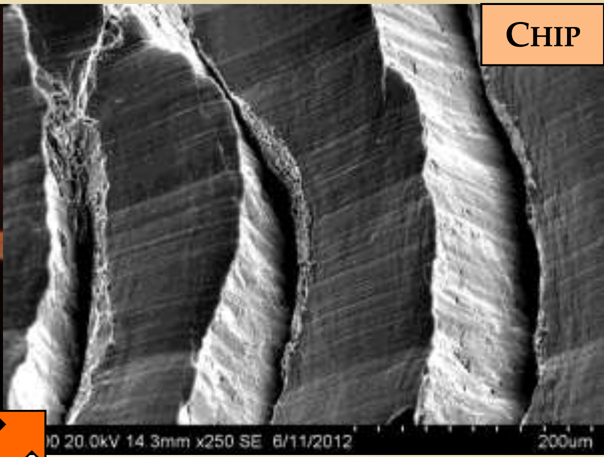
Continuous Ti-64 turning chip

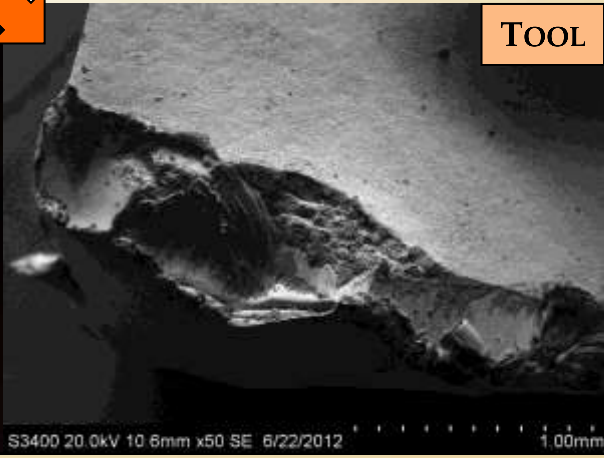
Machining Titanium Alloys

- **Unpredictable & catastrophic tool wear/failure when machining titanium alloys**

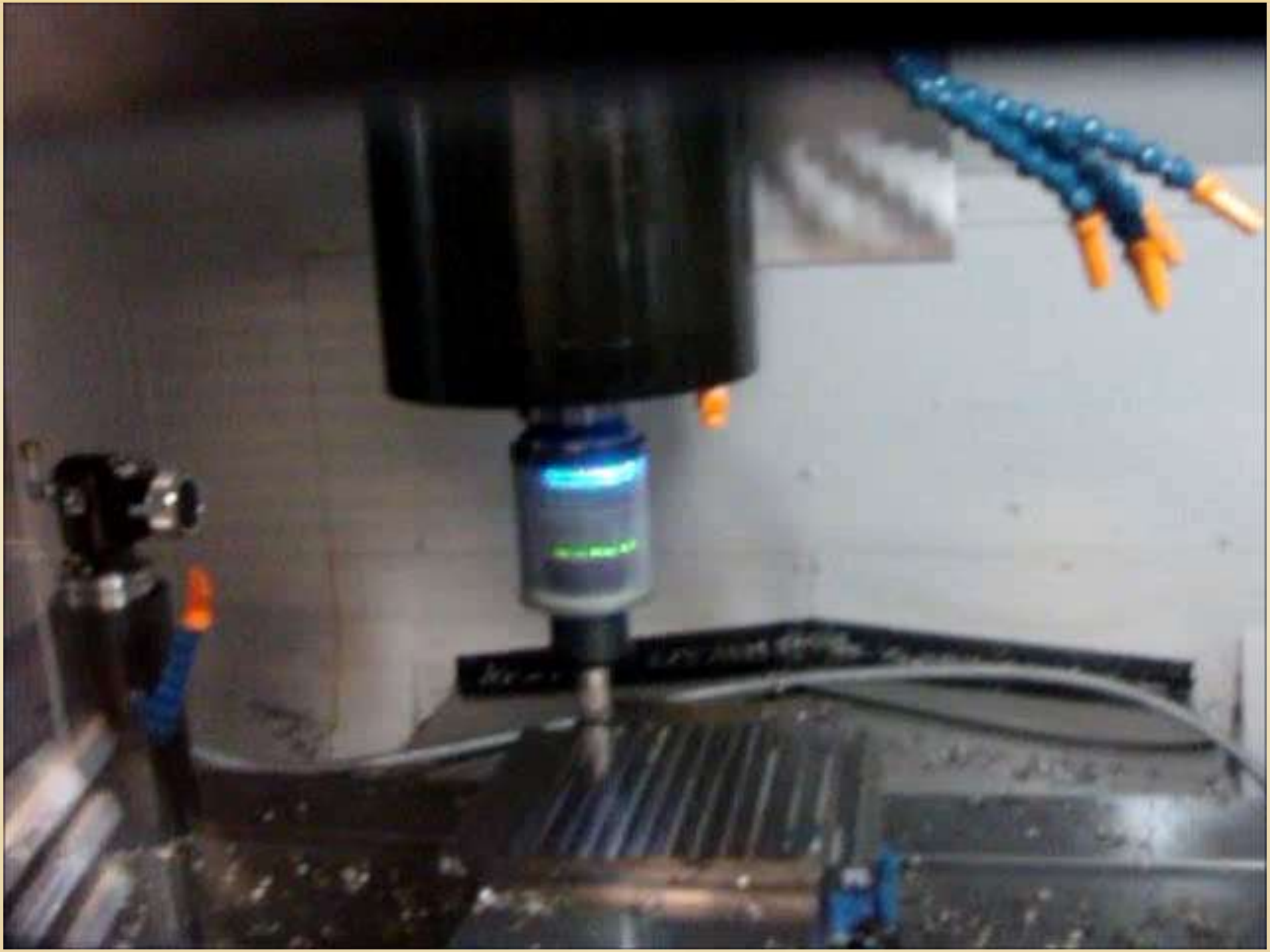
MACHINING TITANIUM ALLOYS







Milling Ti-6Al-4V



The Problem

Superset Problem

Unpredictable & catastrophic tool wear/failure when machining titanium alloys

Solution Approaches

- **Tool considerations:**
  - **Substrates, Coatings, Geometries, etc.**
- **Workpiece considerations:**
  - **μstructures, Alternate grades, etc.**
- **Process conditions:**
  - **Optimum cutting parameters, MQL, HPC, etc.**
- **Non-conventional approaches:**
  - **D/S-P Rotary tools, USM, EAM, etc.**

NIAGARA solid carbide high performance end mill, a few minutes into milling Ti-6Al-4V [5-flute, TiAlN coated, 0.5"(Φ)]

Cost: $ 63.70 (Travers)

However, each approach has drawbacks

Tool Related Issues

- High reactivity with common substrate additives (Ta/TiC) + $$$
- High reactivity with common coatings (TiN, TiCN) + $$$
- Specialized tool geometries ⇨ Limited success + $$$

Workpiece Related Issues

- Machinability focused μstructure modification is not mature + $$$
- Aerospace dominated market has hindered development of 'lower' alternate grades

Process Related Issues

- Even with recommended process variables ⇨ Catastrophic failure
- Advanced coolant delivery ⇨ Is promising, but high setup $$$

Non-conventional Approach Related Issues

- Still in developmental stages
- Additional setup & equipment requirements ⇨ $$$

MOTIVATION

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WC

- High performance tool substrates exist (CBN/PCD)
- Straight uncoated WC 'throwaway' inserts ⇨ Still most economical!
- WC-Co ⇨ Traditionally 'accepted' tooling solution for industry
- Aerospace tooling frequently avoids coatings to prevent contamination

TI-64

- Ti-6Al-4V is the workhorse alloy (~ 50% of production)
- Automotive OEMs use material suppliers over new grade development

COST DRIVERS + INDUSTRY REQUIREMENTS substantiate studying this popular tool -workpiece combination (tribosystem)

SUPERSET PROBLEM

Unpredictable tool wear/failure when machining Ti-alloys

⇨

BOUNDING PROBLEM

Prediction of wear/failure in the WC-Co / Ti-6Al-4V tribosystem

Ti-64 / WC: Microstructure & Properties

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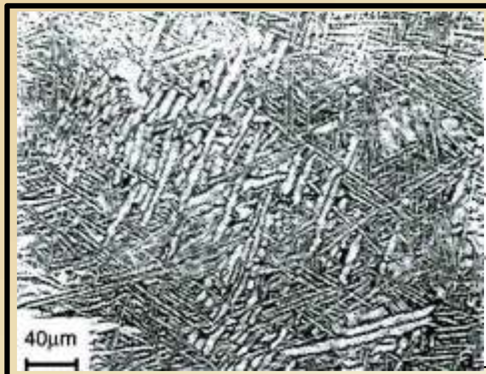
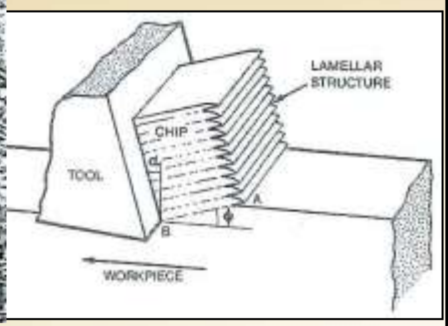
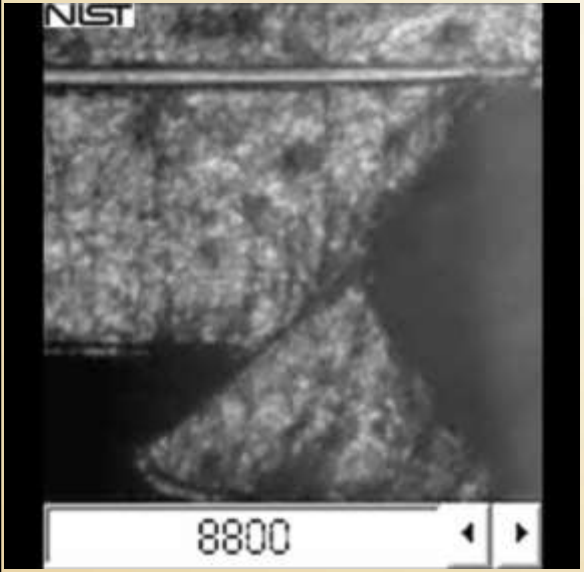
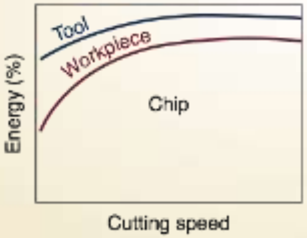
Ti-6Al-4V





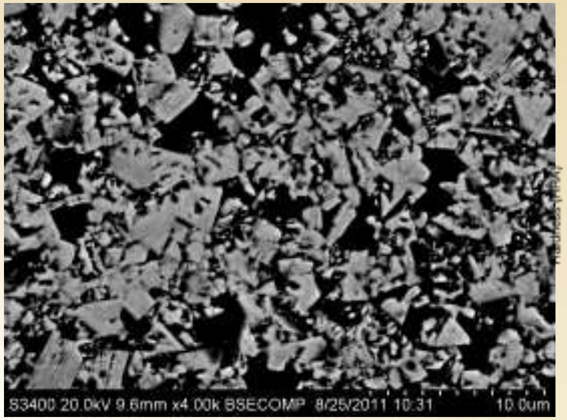


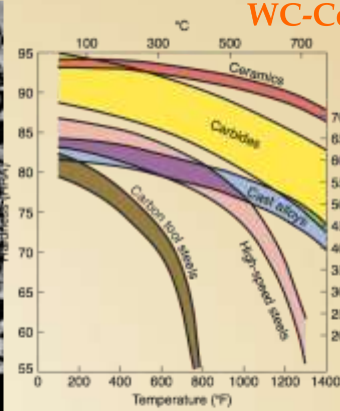
$$T = u\left(\frac{Vt}{k\rho c}\right)^{0.5}$$

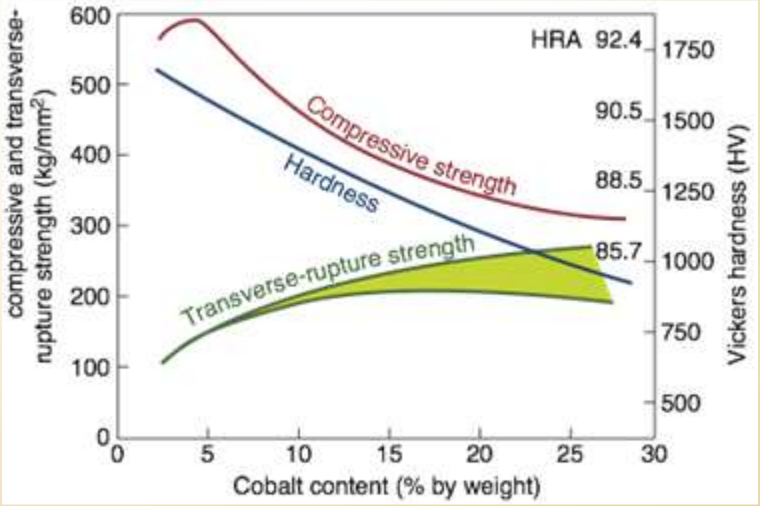


For Ti-6Al-4V, heat into tool ~ 80%

WC-Co

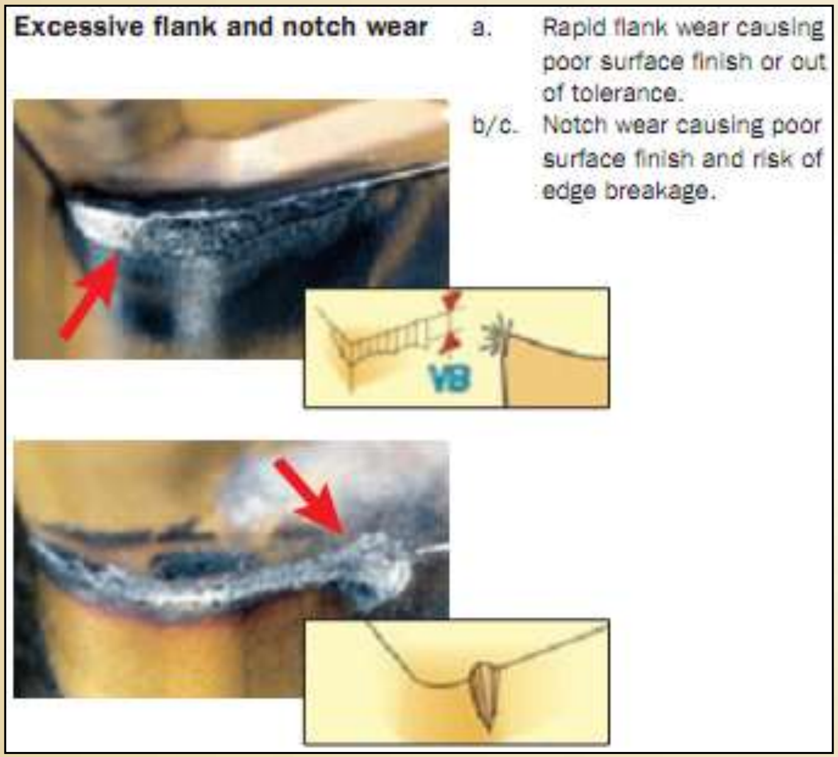






Tool Wear/Failure: Mechanisms & Assessment

- Tool deterioration: Wear, brittle failure, plastic deformation
- Wear mechanisms: Adhesion, abrasion, chemical wear , diffusion



TOOL WEAR MODELING: TRADITIONAL/RATE MODELS

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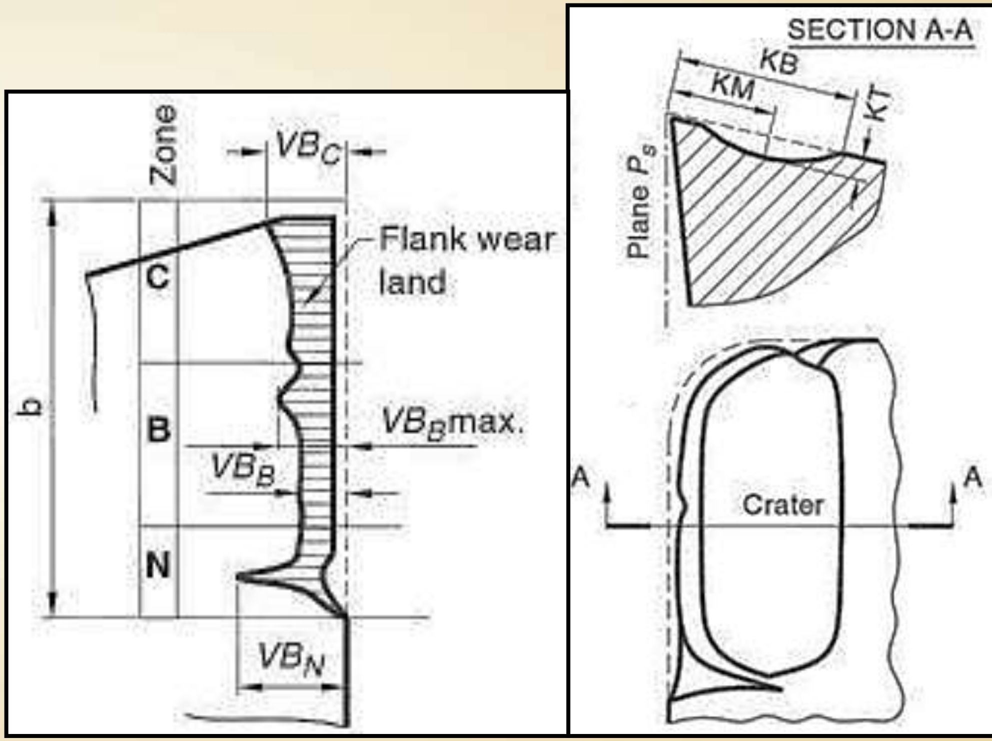
- Empirical tool life models: Taylor/extensions ⇨ *f* (empirical constants)
- General set of recommendations for machining Ti-alloys: Sharp tools, High positive rake, HPC, Arc of engagement, etc.
- Wear rate models: [volumetric wear per unit contact area per unit time]
  - Adhesive wear [Usui]: $\dot{W}_{Ad} = K\sigma_n V e^{-(\alpha/T)}$
  - Abrasive wear [Rabinowicz]: $\dot{W}_{Ab} = C_1\sigma_n VL$
  - Diffusive wear [Arrhenius type]: $\dot{W}_{Df} = C_2 e^{-(\Delta E/kT)}$
  - Chemical dissolution wear [Kramer]
- Conflicting approaches regarding dominant wear modes in Ti-6-4
- Single wear mode models & other time/rate models do not predict well

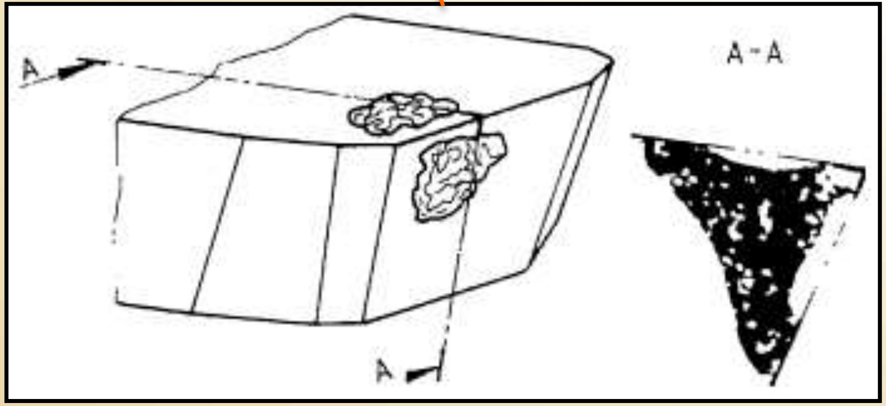
Traditional Assessment of Tool Wear

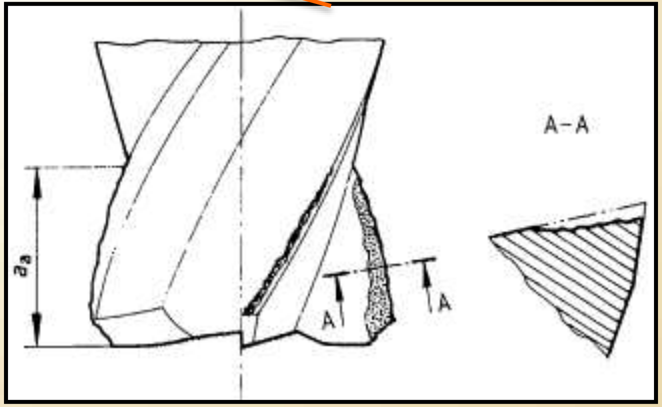
- **Wear profiles characterized as crater wear, flank wear, notching, etc.**
- **Tool life ~ limiting measures of VB/KT (in minutes of cutting time)**
- **Tool life ~ limiting values of:**
  - Surface finish
  - Cutting forces
  - Vibration amplitude
  - Dimensional accuracy, etc.
- **Standard measure for carbide life:**
  - $VB_B \sim 0.3$ mm (or) $VB_{Bmax} \sim 0.6$ mm
  - $KT \sim 0.06 + 0.3f$



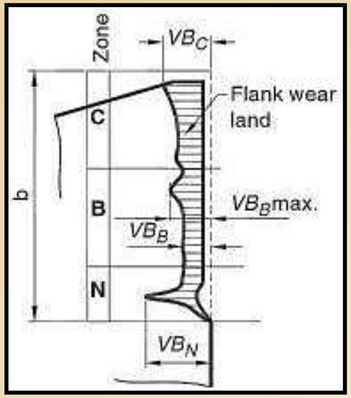
Tool Deterioration Phenomena (Milling): ISO 8688-1/2

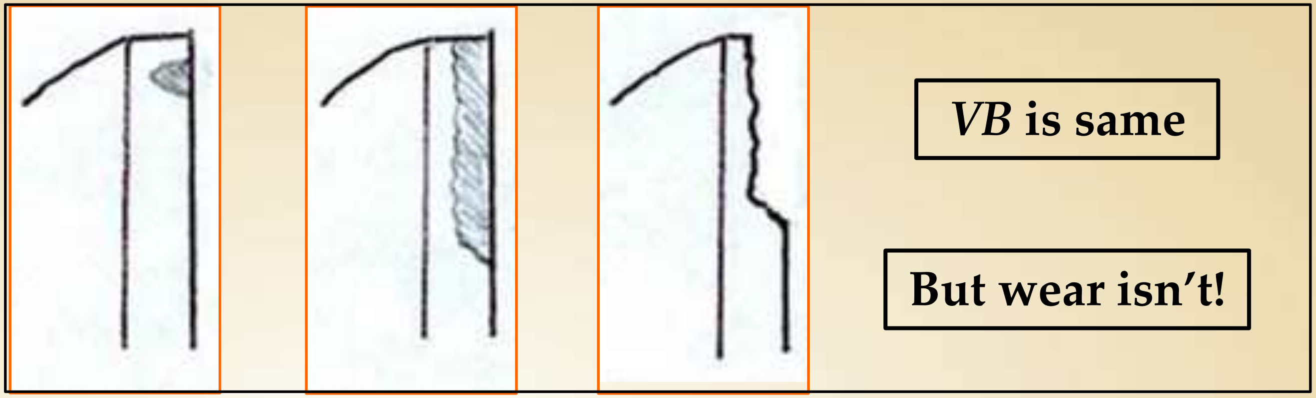
- **ISO coding system for tool life calculation in milling:**
  - **<u>Face milling</u>: 16 distinct tool deterioration phenomena**
    - <u>VB</u>: VB1, VB2, VB3; <u>KT</u>: KT1, KT2; <u>CH</u>: CH1, CH2, CH3, CH4; BF; <u>CR</u>: CR1, CR2, CR3; FL; PD; CF
  - **<u>End milling</u>: 13 distinct tool deterioration phenomena**
    - <u>VB</u>: VB1, VB2, VB3; <u>KT</u>: KT1, KT2; <u>CH</u>: CH1, CH2, CH3; FL; <u>CR</u>: CR1, CR2, CR3; CF
- **Tool wear status ⇨ A diverse combination of these parameters**





MOTIVATION





- This is just one among the many inconsistent scenarios
- G.E. Dieter ⇨ Describes machining tool wear as "*difficult to define without ambiguity*"
- Issues very pronounced for low machinability alloys, *e.g.*, Ti-6Al-4V

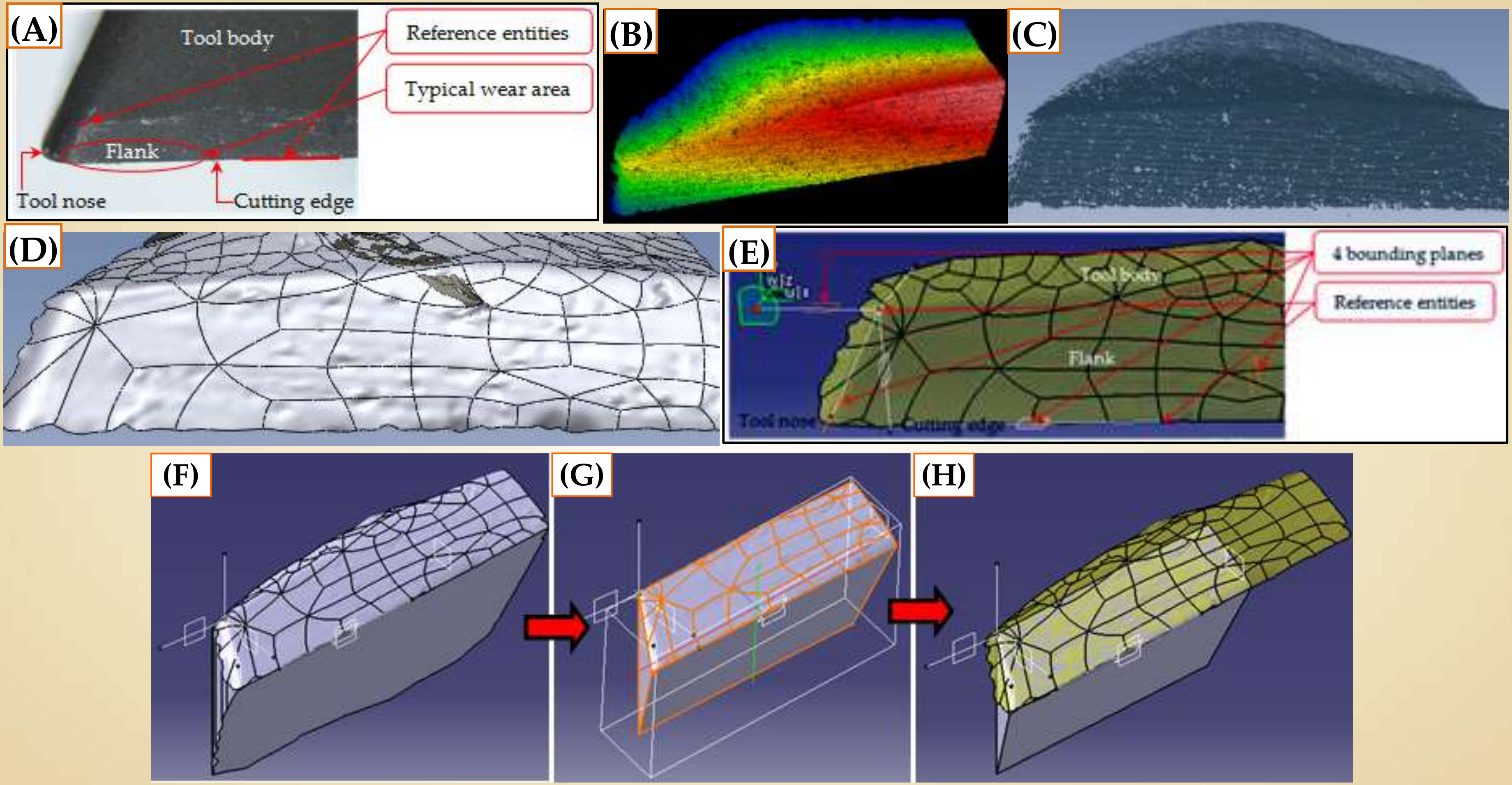
BOTTOM LINE: A MORE VERSATILE TOOL WEAR ASSESSMENT METHOD IS NEEDED!

1. VTW: Need, Characterization & Validation

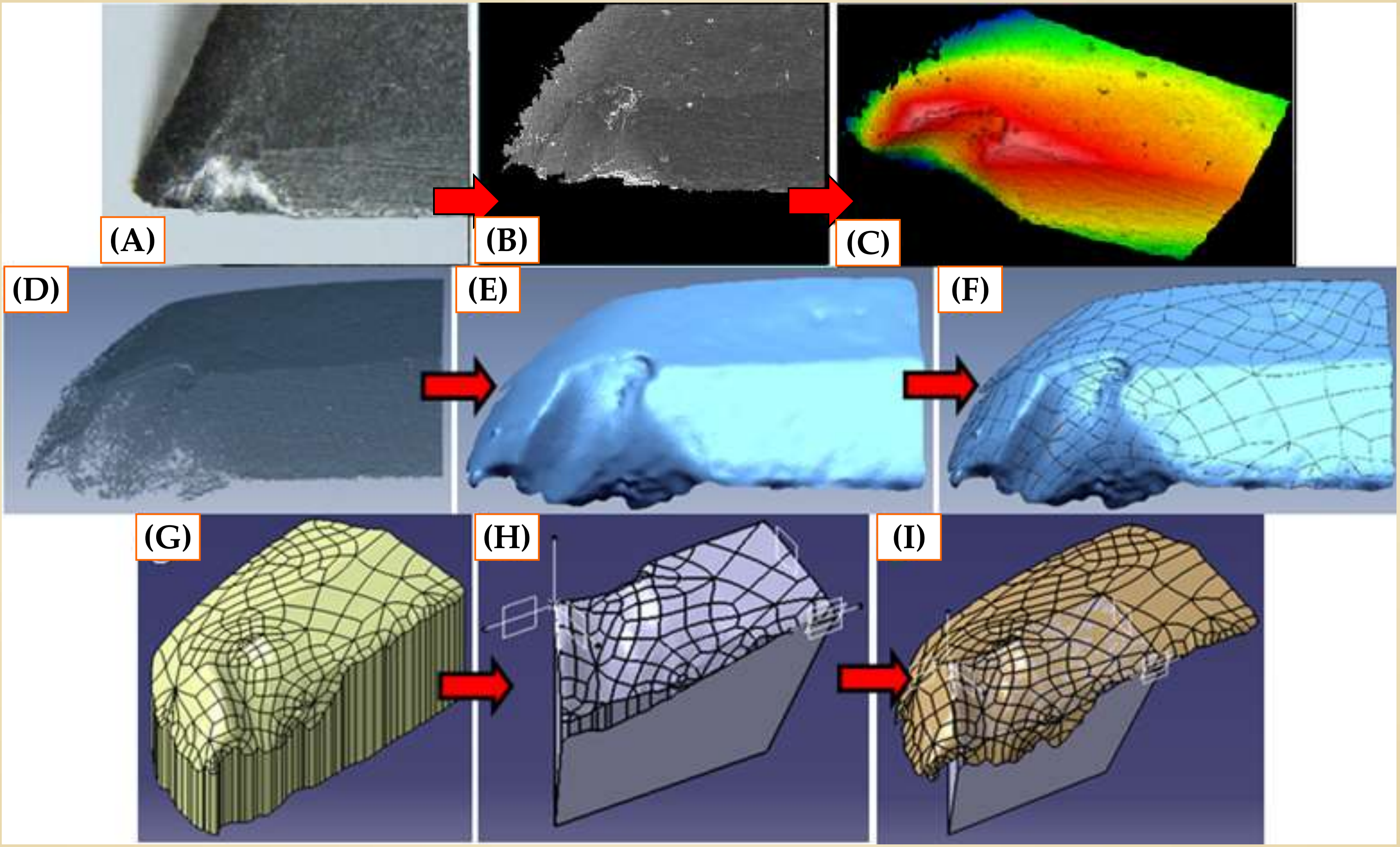
- Wear is a 3D phenomenon ⇨ Measure wear in 3D!
- VTW: Tool insert wear in terms of the actual tool volume worn away
  - Absolute volumetric wear in mm^3 of flank, crater, notch, or other portions
  - Can be catered to insert type & on the fly to wear status, dominant mode, etc.
- Methodology: Identify retained reference entities & cordon off a volume
  - Calculate progressive wear by subtracting calculated retained tool volumes

- Tough grade inserts with positive, helical cutting edges & polished rake for heavy milling of high temperature alloys
- Inserts: ISCAR HM90 APCR 100304PDFR-P IC928

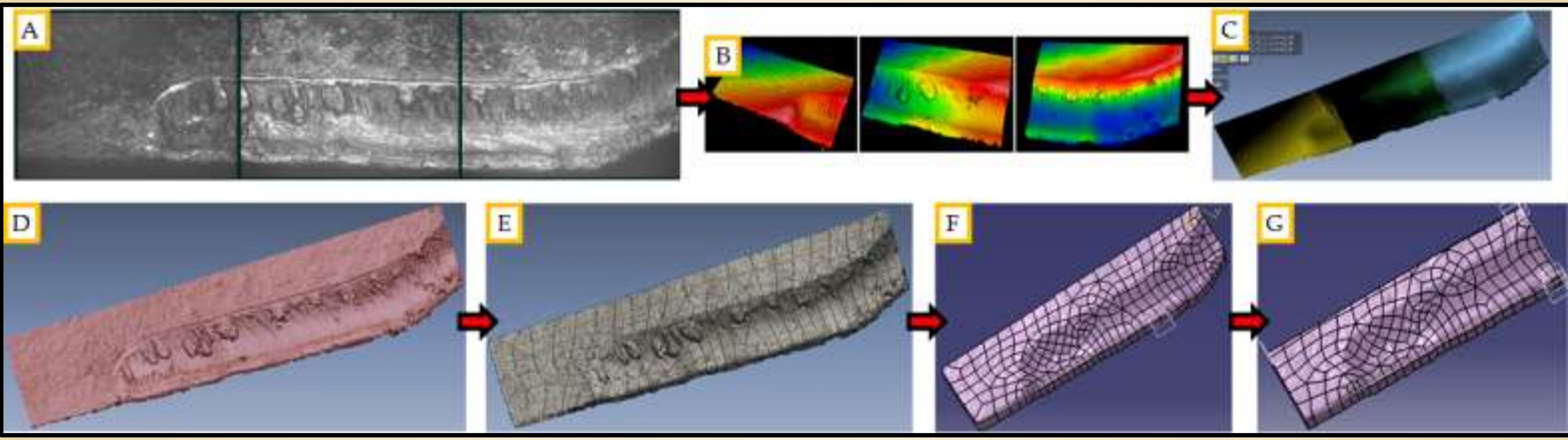
1. VTW: Need, Characterization & Validation



1. VTW: Need, Characterization & Validation

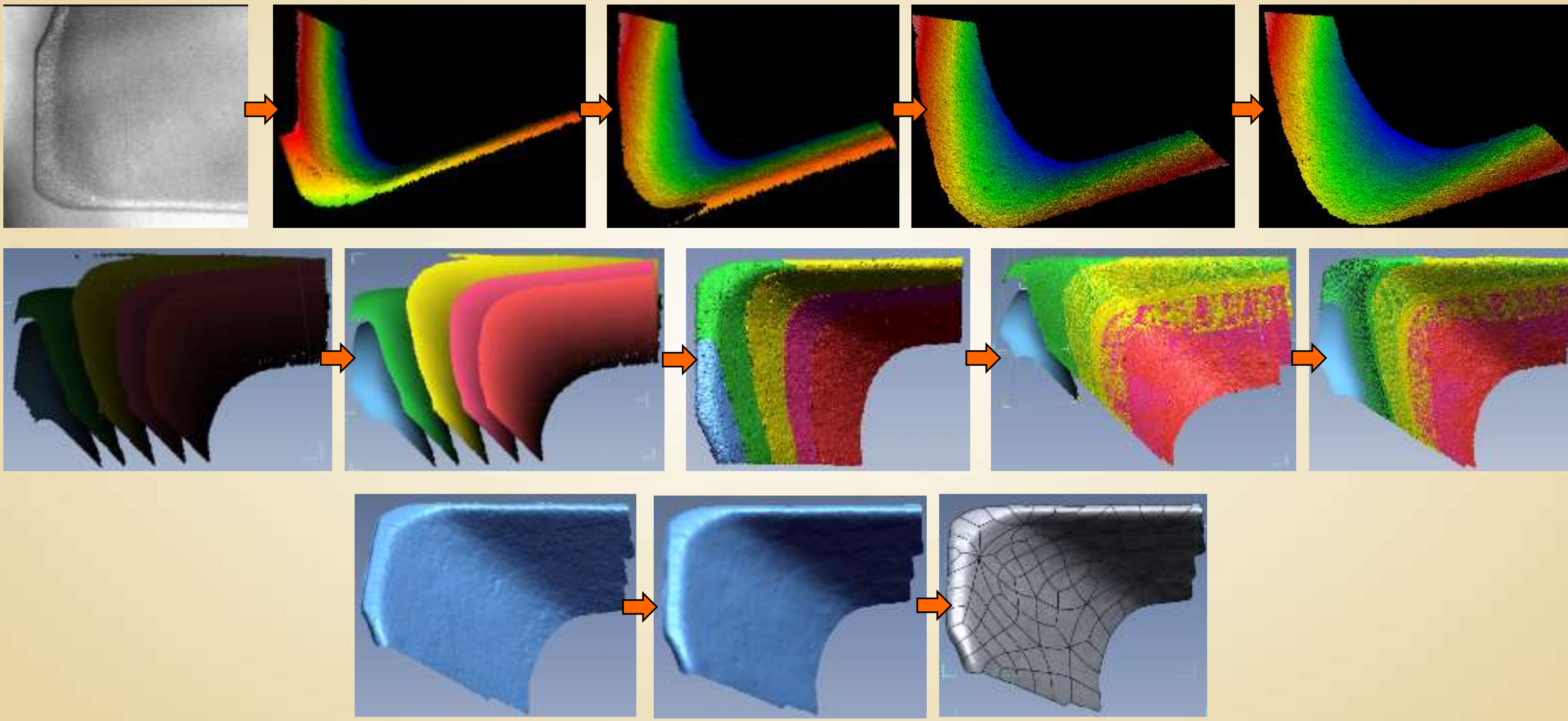


1. Quantification of VTW

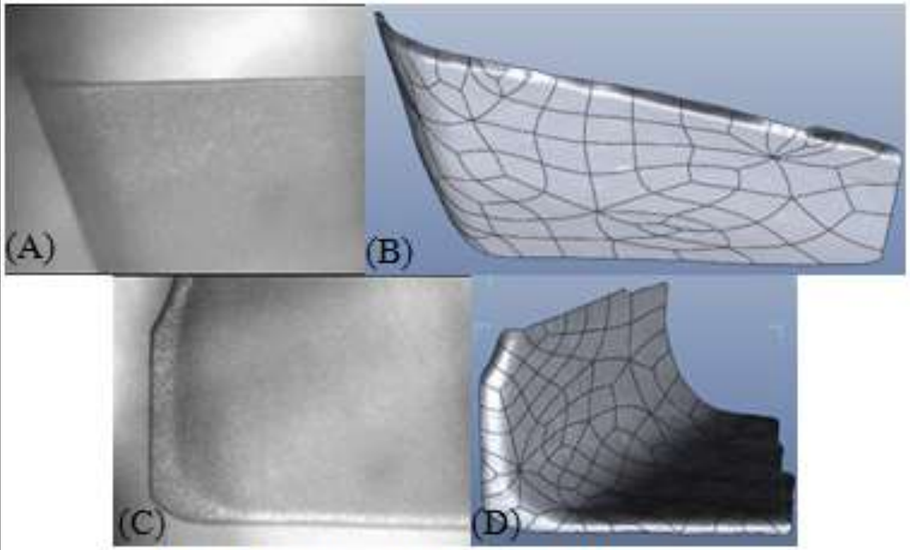


1. VTW: Multiple Scans for Large Scan Heights

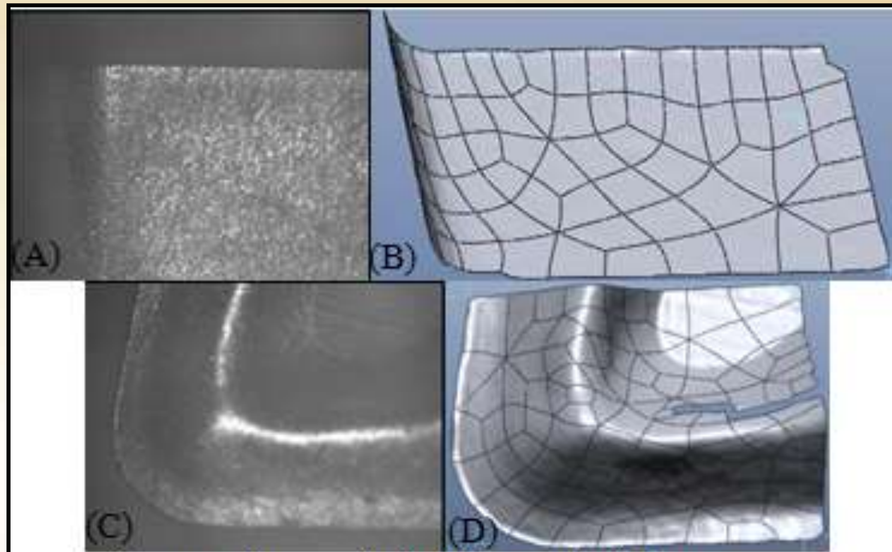
- **ISCAR IC-28 milling insert [New] [Uncoated] [Rake face – crater area]**



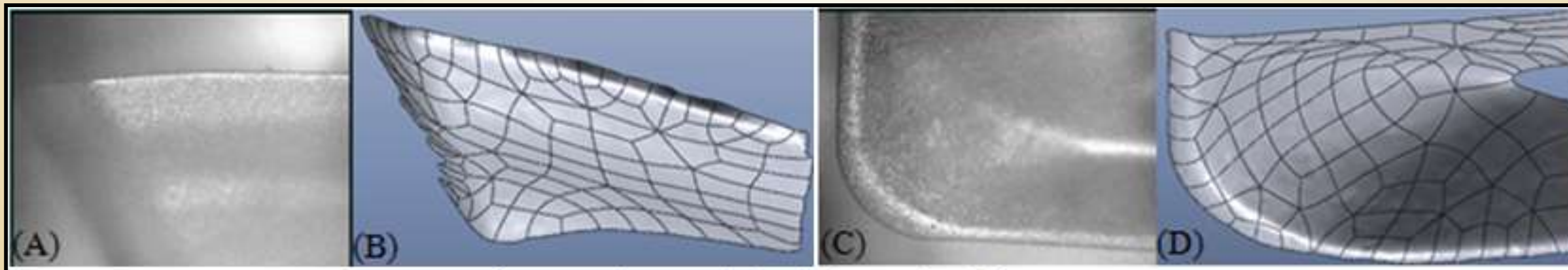
1. Applicability to a Variety of Complex Insert Shapes



ISCAR IC-28: (A,B) Flank, (C,D) Rake faces



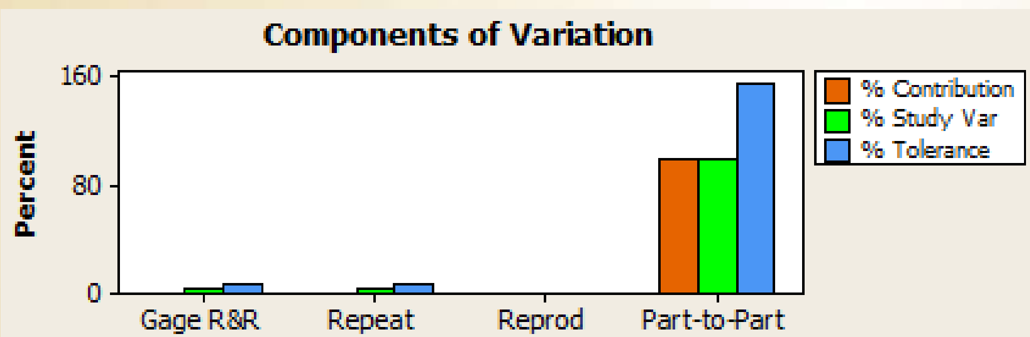
Sandvik (turning): (A,B) Flank, (C,D) Rake faces



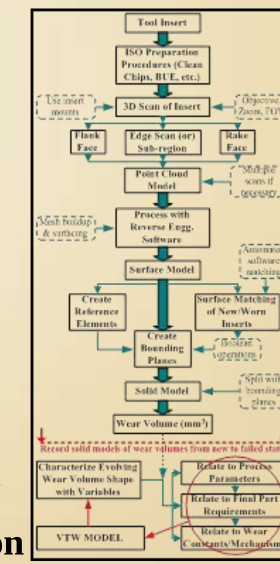
Sandvik (milling): (A,B) Flank, (C,D) Rake faces

1. VTW: Measurement System Validation (Gauge R&R)

- ANOVA Gauge R&R: To assess the amount of measurement system variability (operator, equipment & methodology)
- 2 operators * 2 repetitions each * 5 tool insert measurements
- All 5 milling inserts: Same type [1 new, 3 worn, 1 failed]
- Gauge R&R showed <7% total variation due to measurement error
- High part-to-part variation is due to different levels of wear



- Ongoing work: Wear mass validations



Methodology Standardization

1. Concept of the M-Ratio

- **Similar concept as G-Ratio in Grinding**

$$\text{M - Ratio} = \frac{\text{Volume of Material Removed}}{\text{Volume of Tool Insert Worn}}$$

- **Changing efficiency of the insert in each pass for the same MRR**

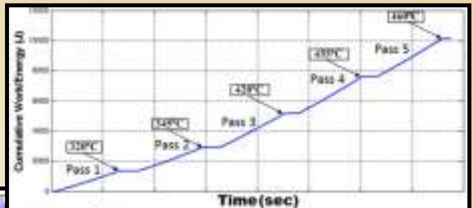


Figure 17: Cumulative work done by the cutting insert

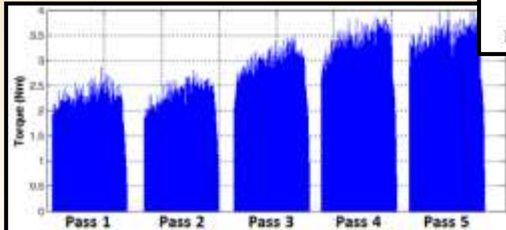


Figure 16: Cutting torque during each pass

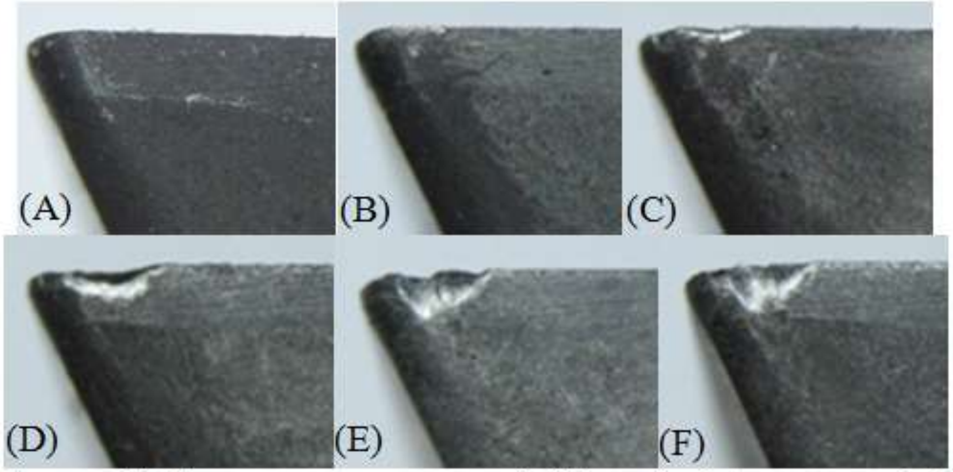


Figure 13: Evolving flank wear (A) New, (B-F) After pass 1-5

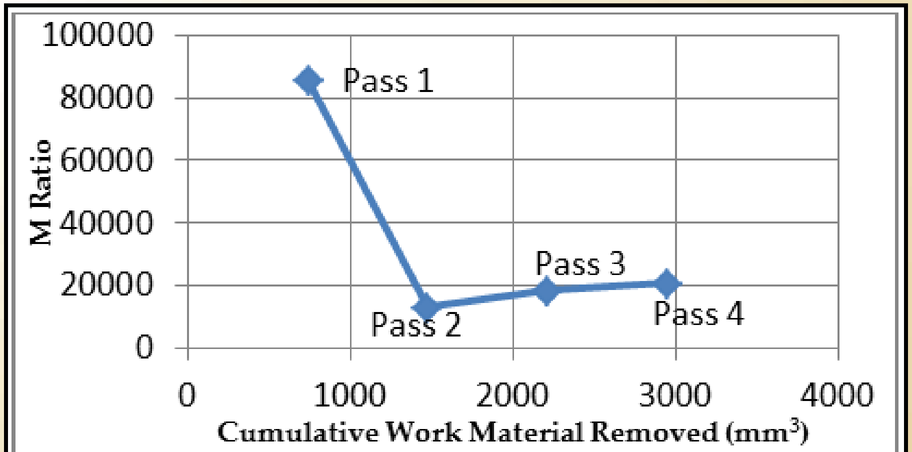
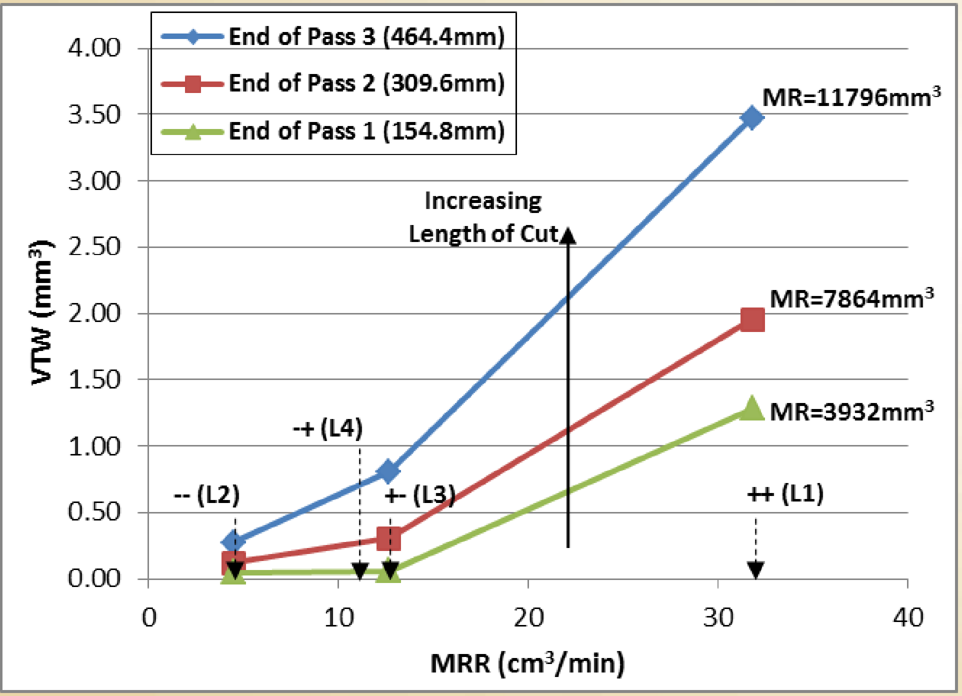


Figure 15: M-Ratio at the end of each pass (Pass 5 – Failed)

2. Relationships with Wear Rate & Energy

Experimental Setup	Parameters	
	Speed (m/min)	Feed (mm/rev)
1 (L1)	200	0.5
2 (L2)	70	0.2
3 (L3)	200	0.2
4 (L4)	70	0.5

Pass	Cumulative Length of Cut (mm)	Cumulative Stock Volume Removed (mm^3)	Tool Material Worn (mm^3)			
			Setup 1 ++(L1)	Setup 2 --(L2)	Setup 3 +-(L3)	Setup 4 -+(L4)
1	154.8	3931.92	1.29	0.05	0.06	Tool Failure
2	309.6	7863.84	1.96	0.12	0.31	
3	464.4	11795.76	3.47	0.27	0.81	
MRR (cm^3/min)			31.8	4.5	12.7	11.1



- Both VTW & VTW rate are proportional to MRR
- A detrimental wear control factor
- High-feed, low-speed process parameters - Catastrophic

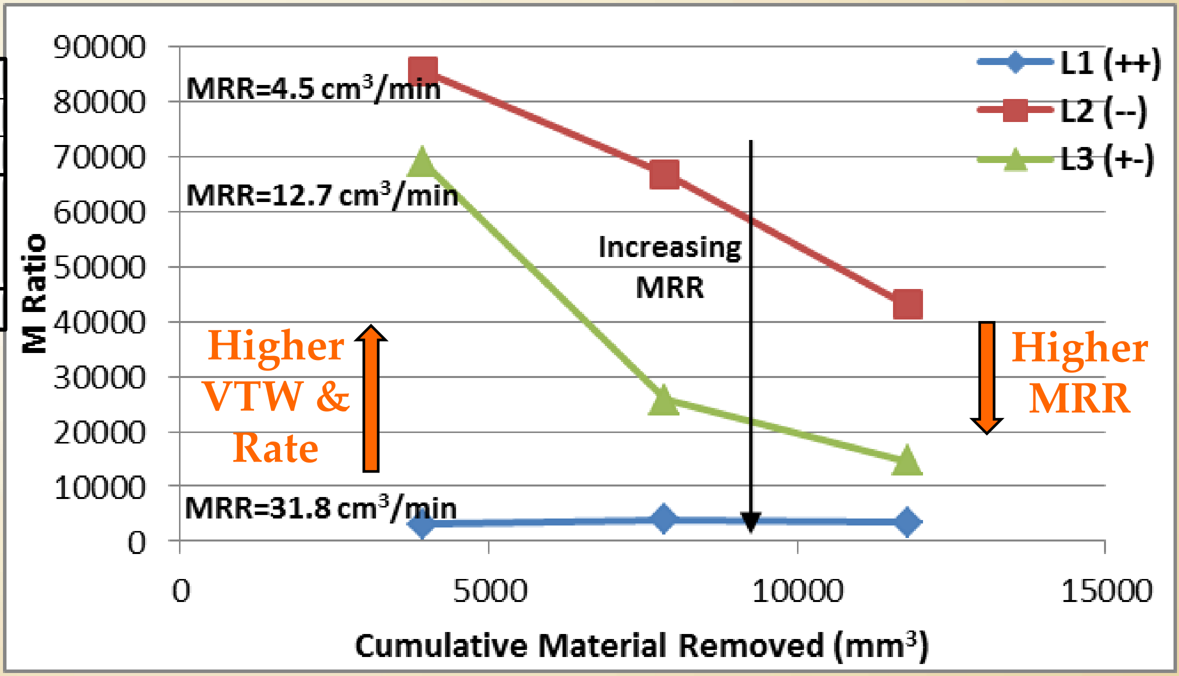
2. M-Ratio vs. MRR

- Newer tool (in pass 1) is more efficient in removing stock (higher M-ratio) than in subsequent passes (pass 2-3)
- Decreasing M-ratio ➔ Decreasing tool efficiency in removing unit stock
- More beneficial to the tool to remove work material at lower MRR

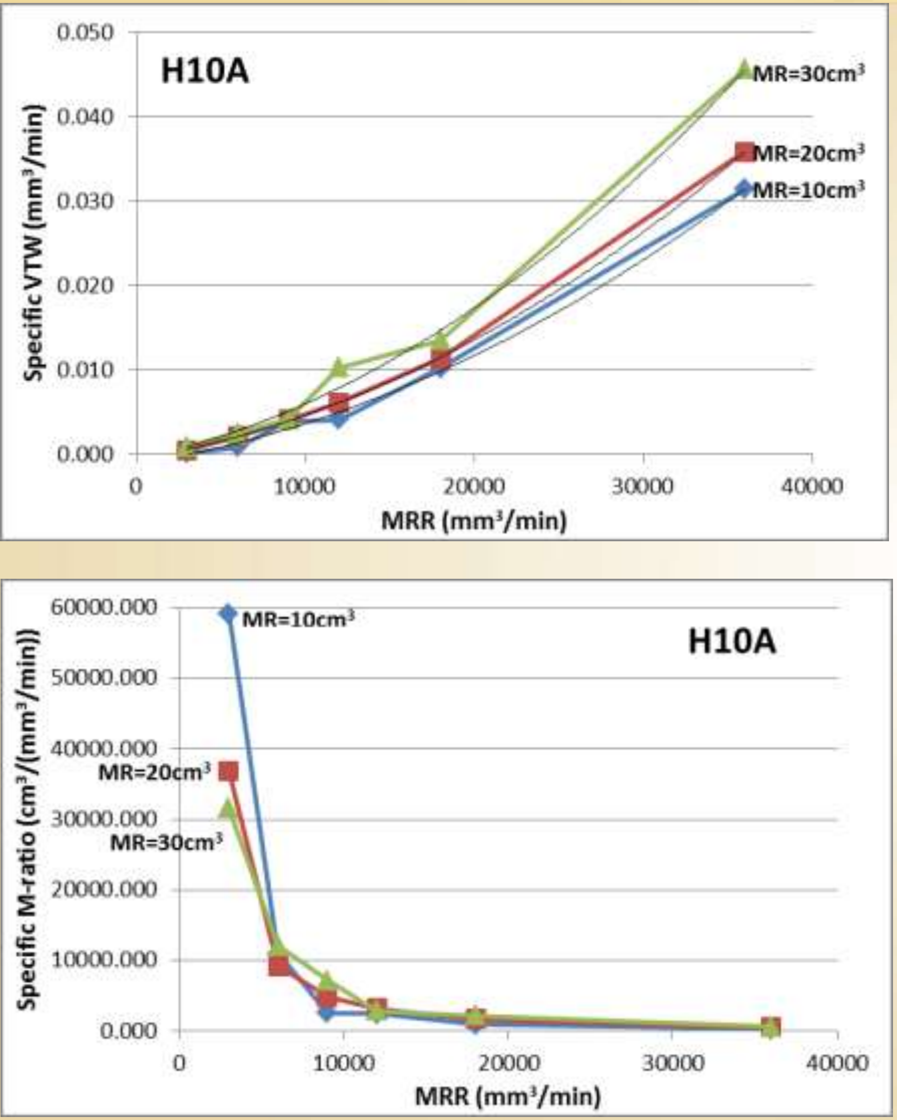
Pass	Cumulative Stock Volume Removed	M-ratio (Stock removed/Tool worn)			
		Setup 1	Setup 2	Setup 3	Setup 4
		++(L1)	--(L2)	+-(L3)	-+(L4)
1	3931.92	3059.86	85476.52	68981.05	Tool Failure
2	7863.84	4022.42	66642.71	25783.08	
3	11795.76	3397.40	43050.22	14616.80	
MRR (cm^3/min)		31.8	4.5	12.7	11.1

$$CF(\$) = f_1\left(\frac{1}{MRR}\right) + f_2\left(VTW(t)\right)$$

3D extension of speed-based cost optimization between *t & VB*

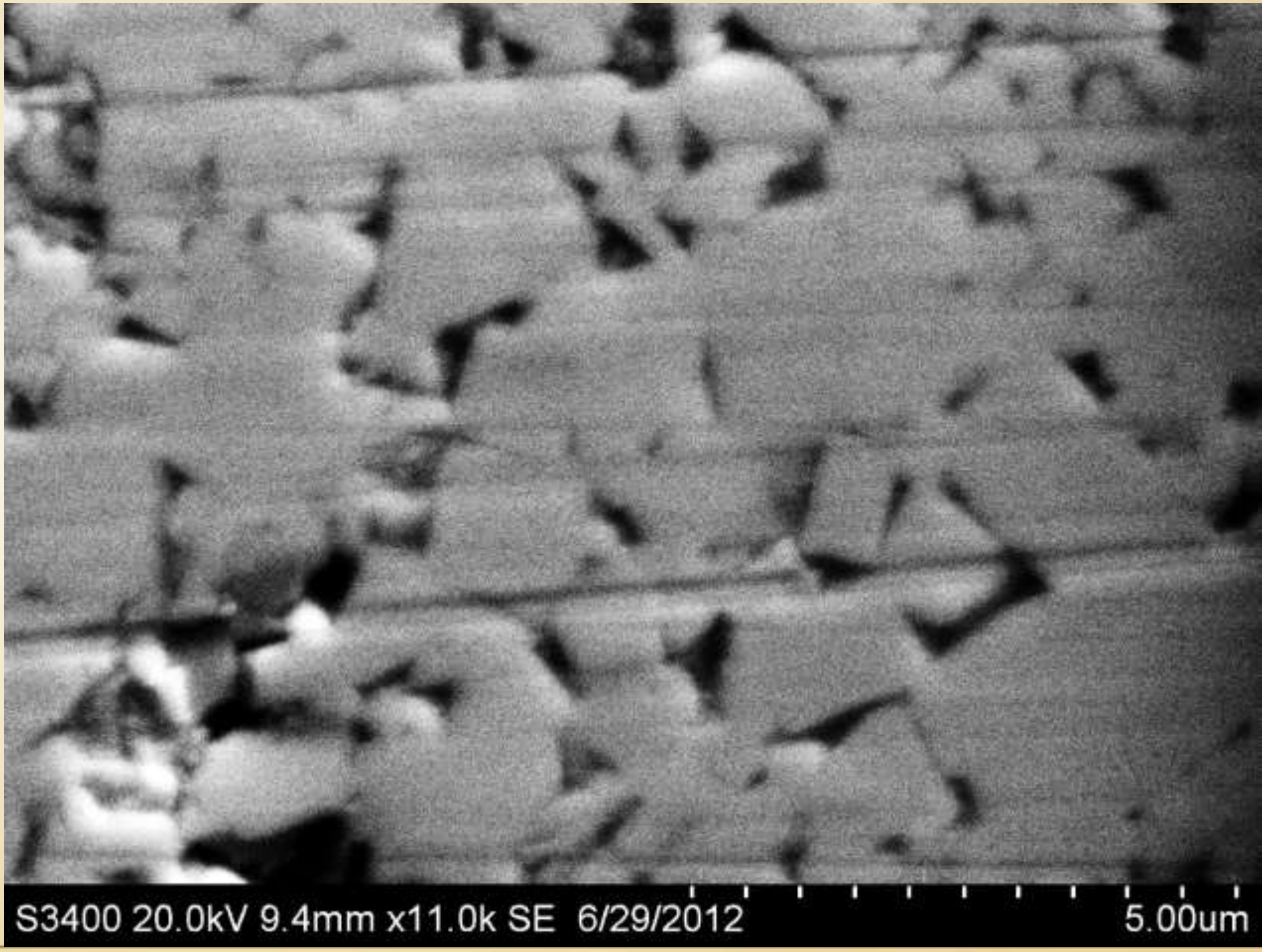


2. Similar for Turning Inserts



3. Primary Micro Factor – Grain Size

- **Sandvik CNGP 12 04 08 H10A**
- **Sandvik CNGP 12 04 08 H13A**



- **d_g (H10A) ~ 0.54 μm**
- **d_g (H13A) ~ 0.61 μm**

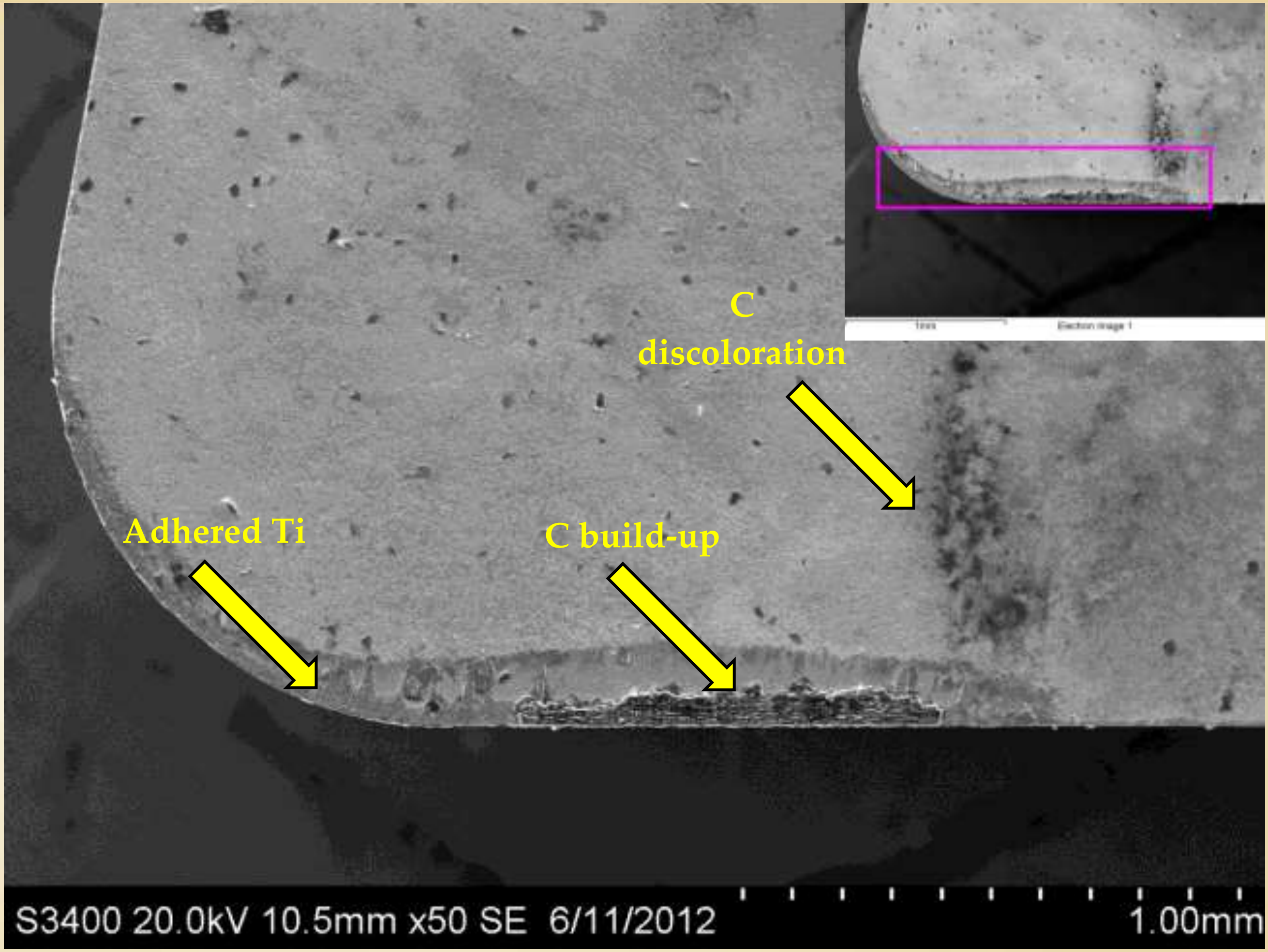
3. Final DOE of Runs

Texas A&M University

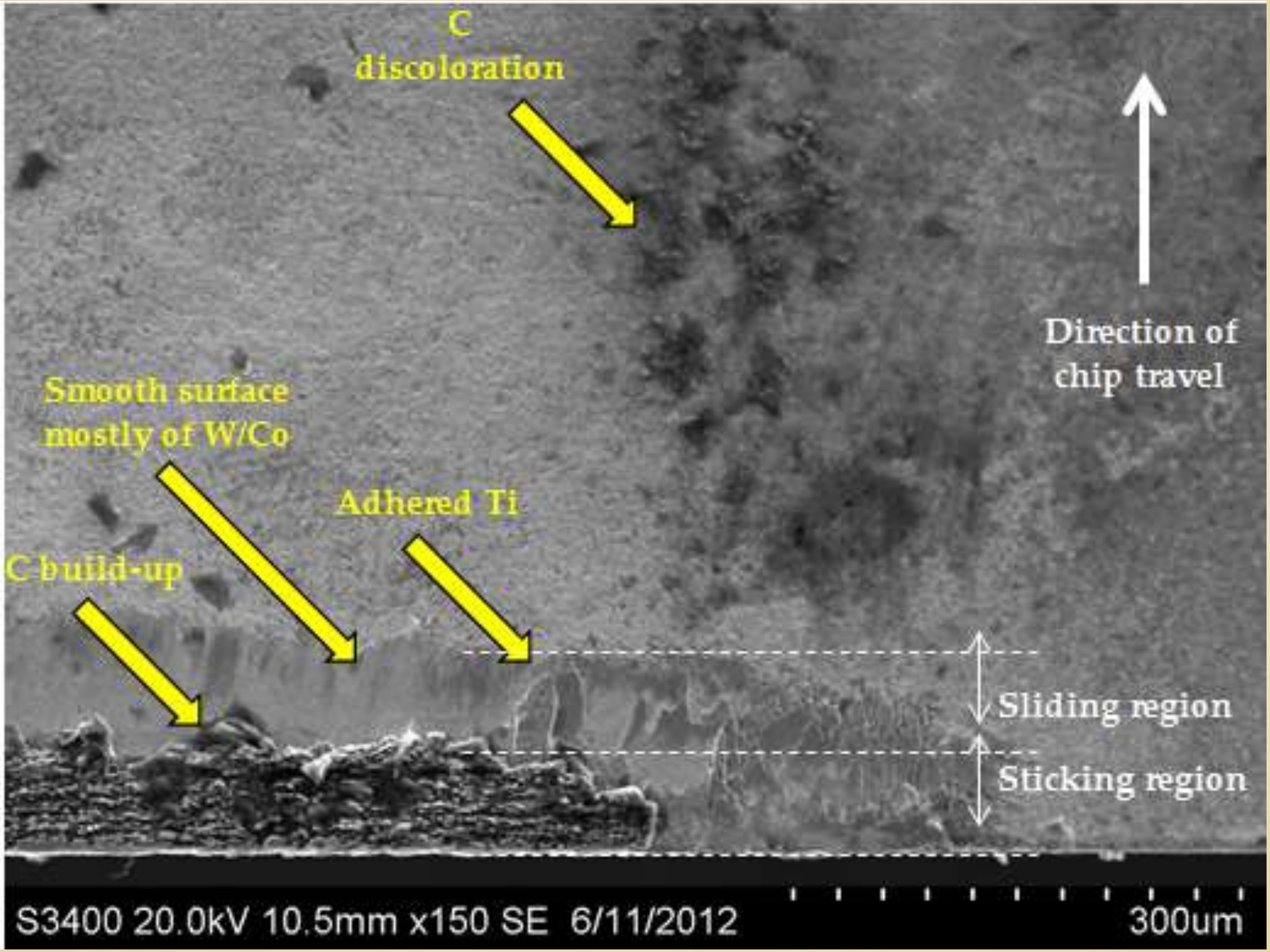
For H10A WC-Co Insert (d_g ~ 0.54 μm)				
Run Info	Process Parameters			Total Cut Stock Volume
Run (#)	DoC (mm)	f (mm/rev)	V (m/min)	
Runs 1 - 9	2	0.05	30	10 cm^3
	2	0.05	60	
	2	0.05	120	
	2	0.15	30	
	2	0.15	60	
	2	0.15	120	
	2	0.30	30	
	2	0.30	60	
	2	0.30	120	
Runs 19 - 27	Same as above			20 cm^3
Runs 37 - 45	Same as above			30 cm^3

For H13A WC-Co Insert (d_g ~ 0.61 μm)				
Run Info	Process Parameters			Total Cut Stock Volume
Run (#)	DoC (mm)	f (mm/rev)	V (m/min)	
Runs 10 - 18	2	0.05	30	10 cm^3
	2	0.05	60	
	2	0.05	120	
	2	0.15	30	
	2	0.15	60	
	2	0.15	120	
	2	0.30	30	
	2	0.30	60	
	2	0.30	120	
Runs 28 - 36	Same as above			20 cm^3
Runs 45 - 54	Same as above			30 cm^3

3. Wear Mechanism Dominance



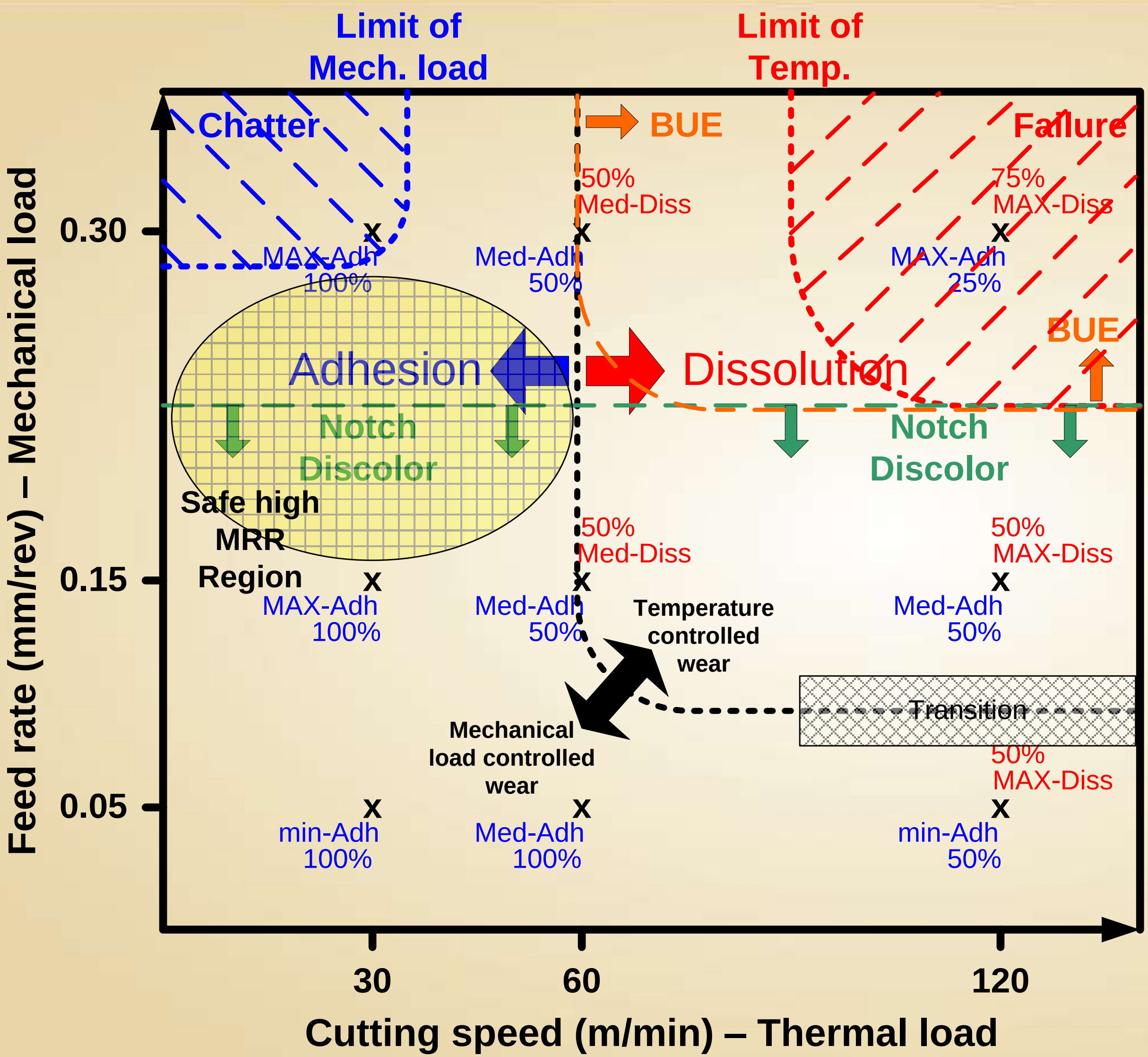
3. WEAR MECHANISM DOMINANCE



3. Main Observations from SEM/EDS of Worn Tools

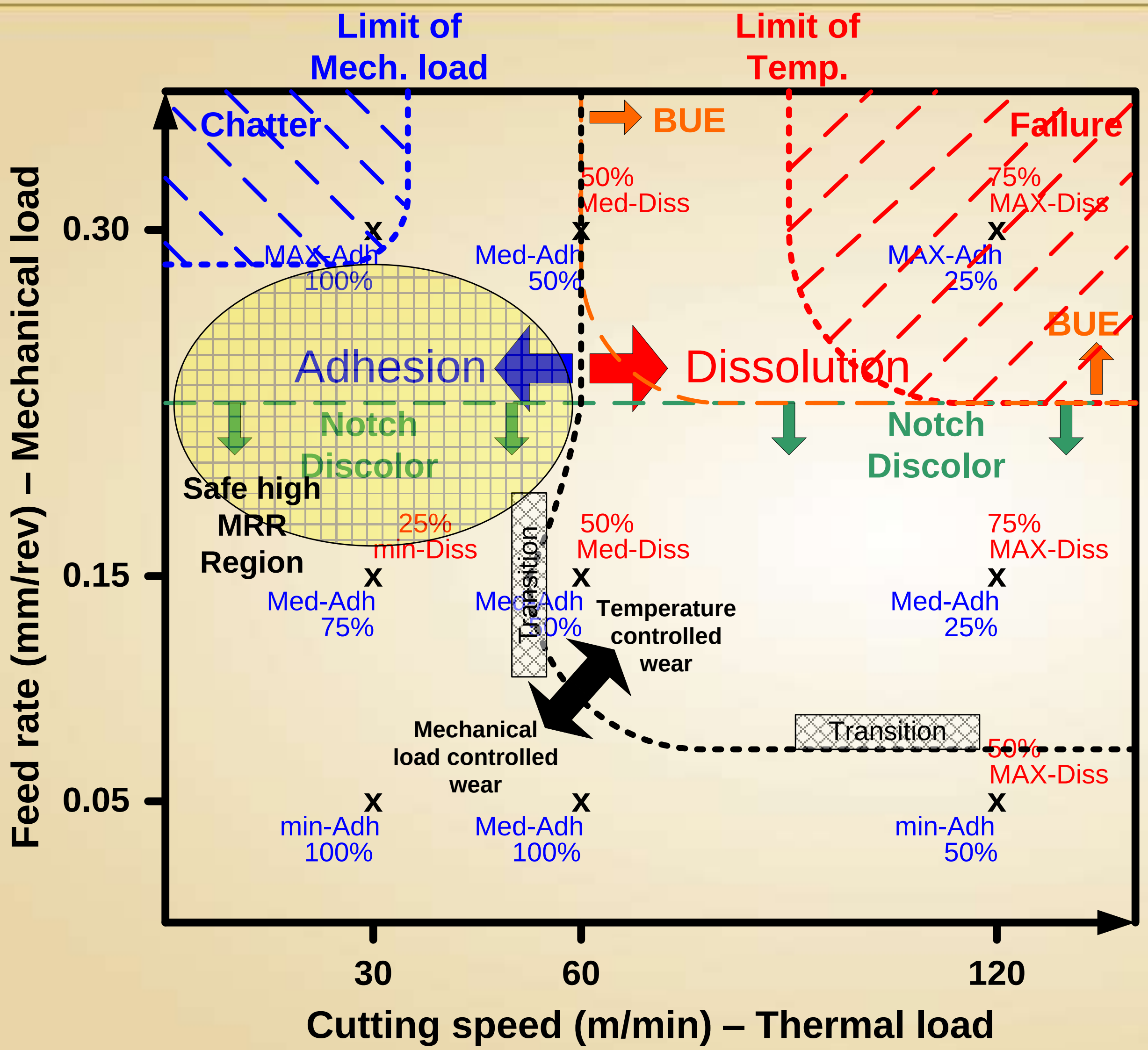
- Adhered Ti at all speeds (prominent at lower V, and decreases with V)
- Smooth surface in trough (high V) ⇨ Generalized dissolution wear
  - Predominantly W & C
  - Chips carry away Co
  - C build-up (“chemically-pulled”)
  - C discoloration only at low/medium V
- No indications of abrasive wear (with uncoated tool)
- Interactions?
- Difference b/w H13A & H10A: Dissolution was more dominant (high V)

3. Wear Mechanism Mapping

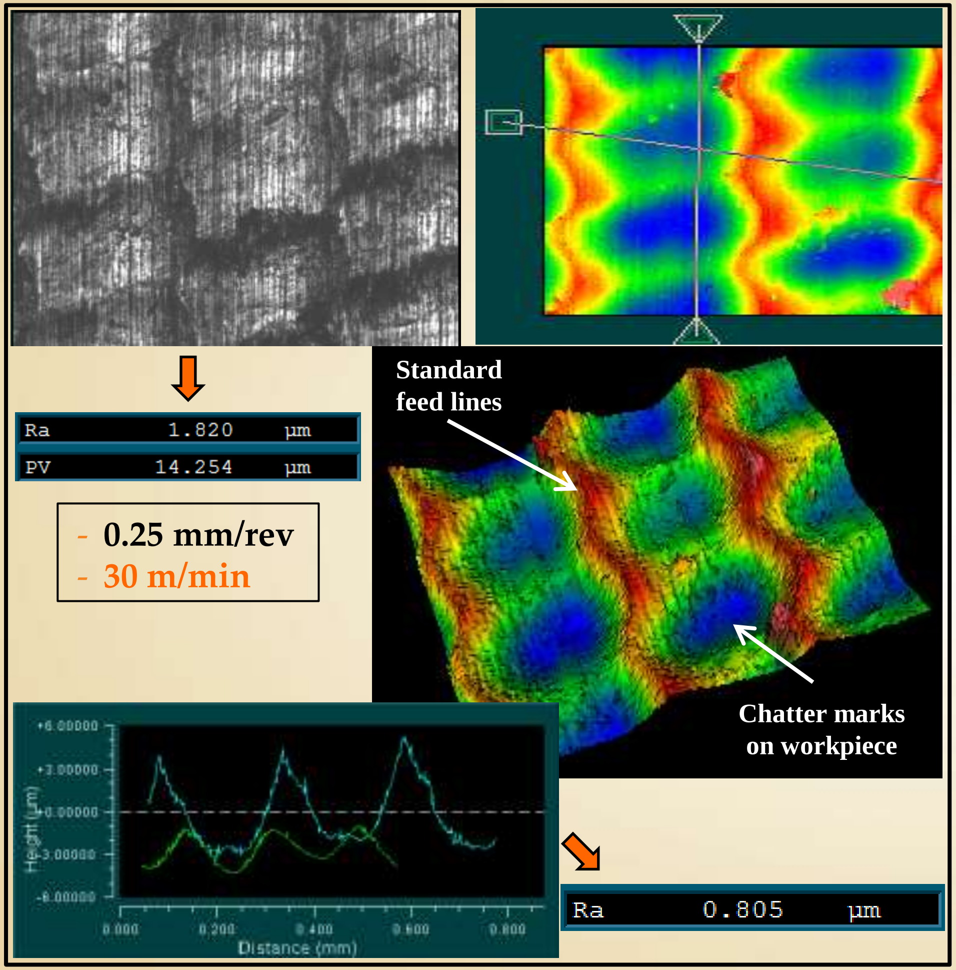


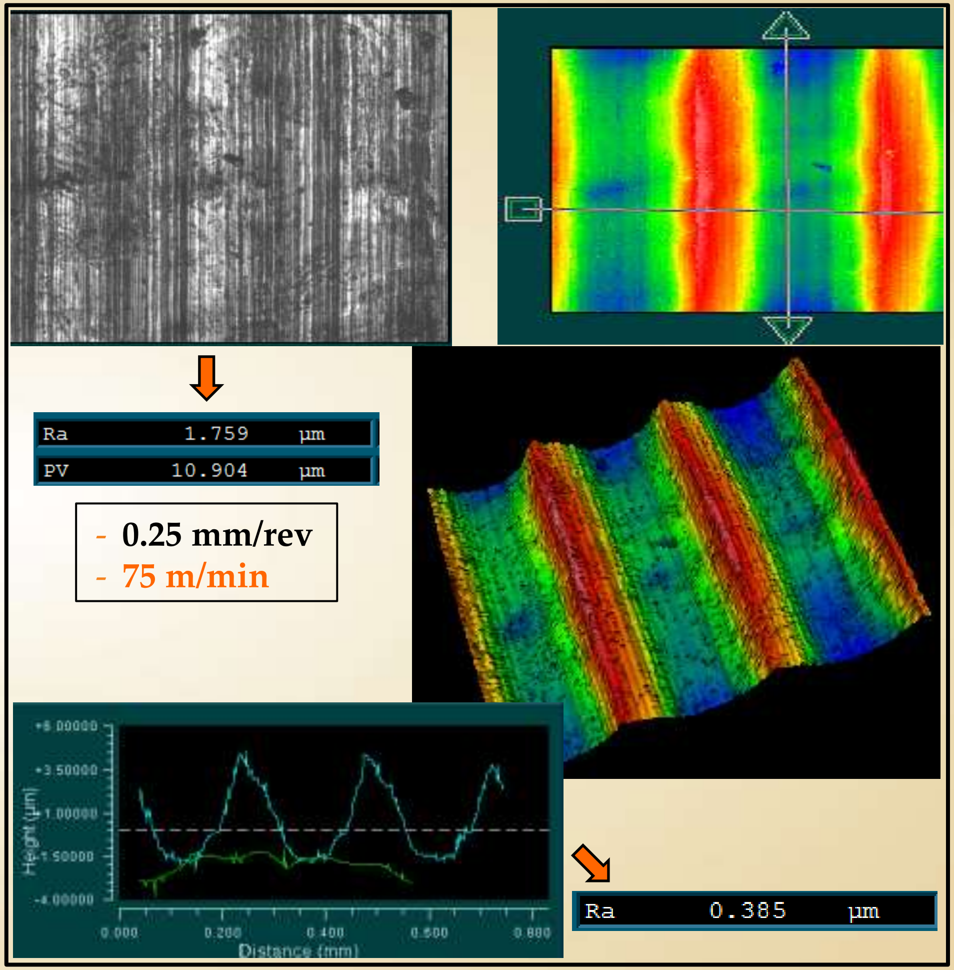
- Mechanical load vs. temperature controlled wear
- Chatter & failure regions
- Adhesion vs. dissolution dominance
- BUE regions
- Safe regions for higher MRR (productivity)

3. Wear Mechanism Mapping



3. CHATTER @ HIGH F & LOW V





4. DOE-HPC PROJECT

- HPC of Cutting Performance Simulation
- Cost-effectively realize the most profitable MRR
- Simulate the multi-variable multi-level design space, identify key variables, validate simulations

1) Cutting Simulation Design
2) Variability Integration
3) HPC Integration
4) HPC Runs
5) Bivariate Analysis
6) Physical Experiment Validation
7) Control Integration

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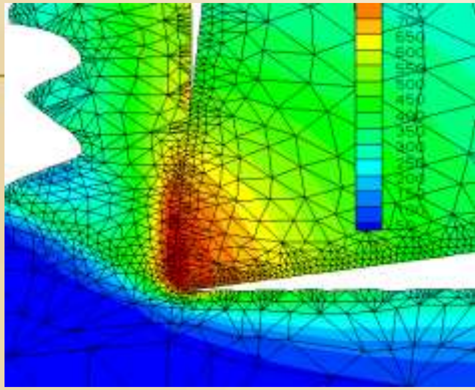
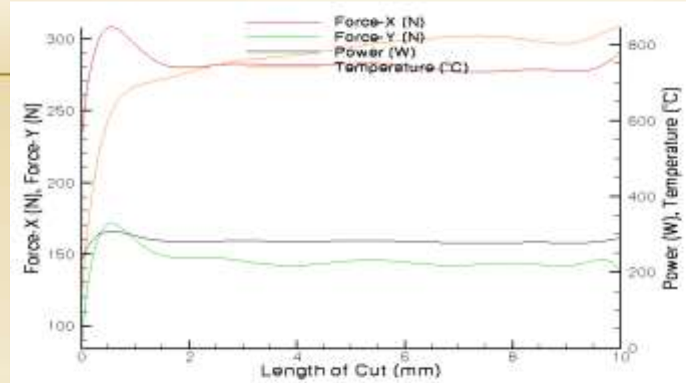
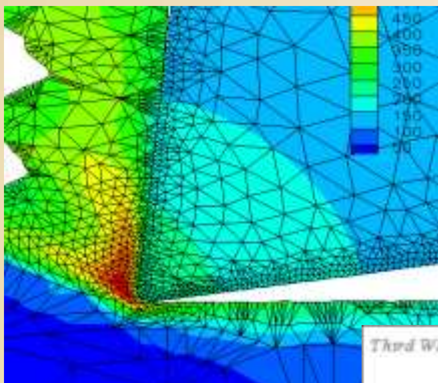
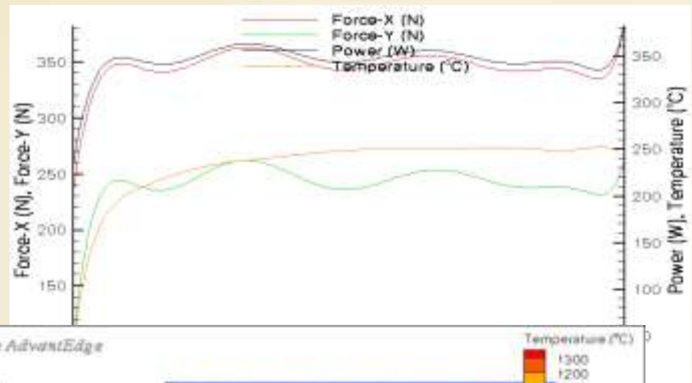
4. DOE-HPC PROJECT

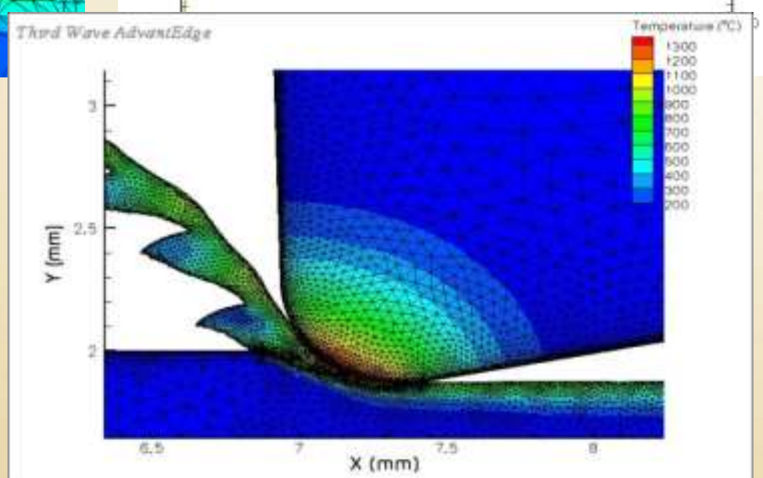


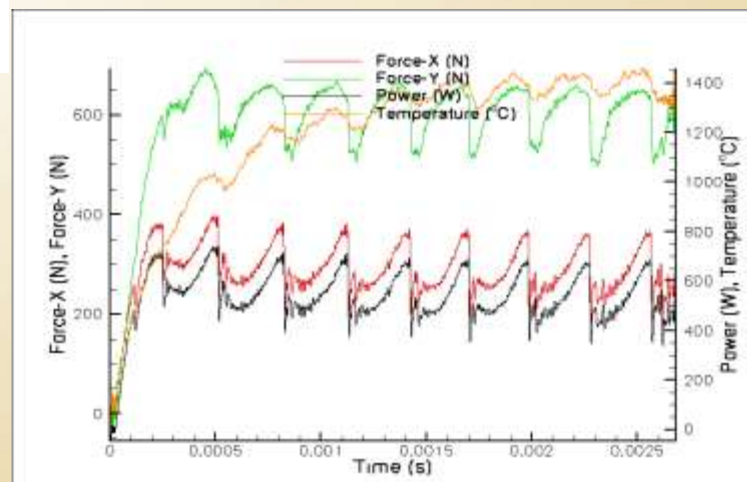


#	Tool Substrate Material	Force Range (Fx/Fy) (N)	Peak Temp. (^{0}C)
1	Carbide-general	280/150	~ 800
2	Ceramic-general	270/140	~ 950
3	CBN	280/160	~ 750
4	PCD (high K)	325/225	~ 250









4. IDENTIFICATION OF PRIMARY FACTORS

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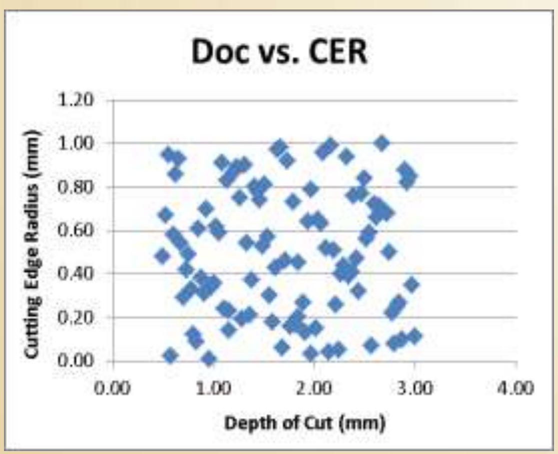
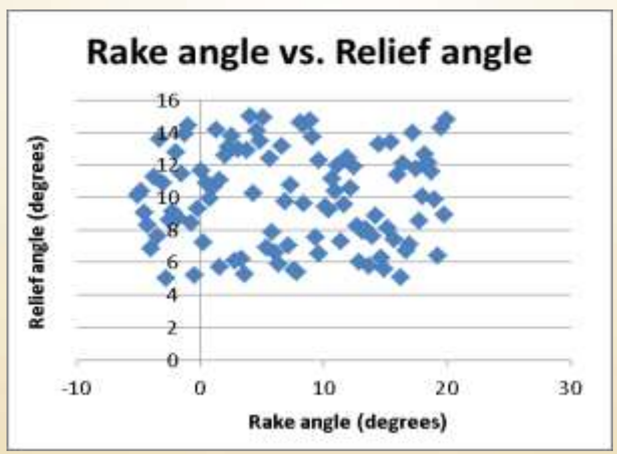
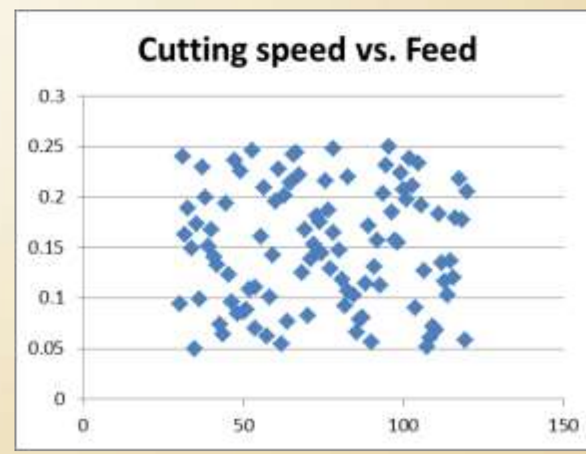
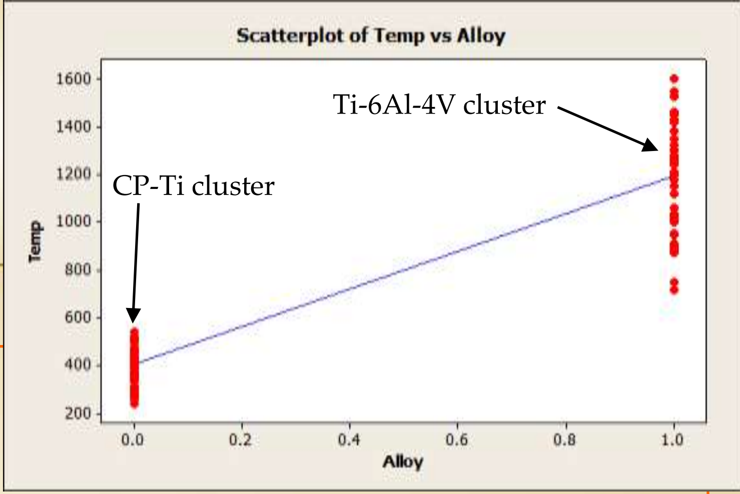
1. Built on peer-reviewed work
2. Master list of tool/process factors ⇨ Subset
3. Formulated an OLH-DOE of 100 runs
4. Conducted machining FEA simulations to identify the primary factors affecting wear mechanics
5. Bivariate analyses of the results from 100 runs



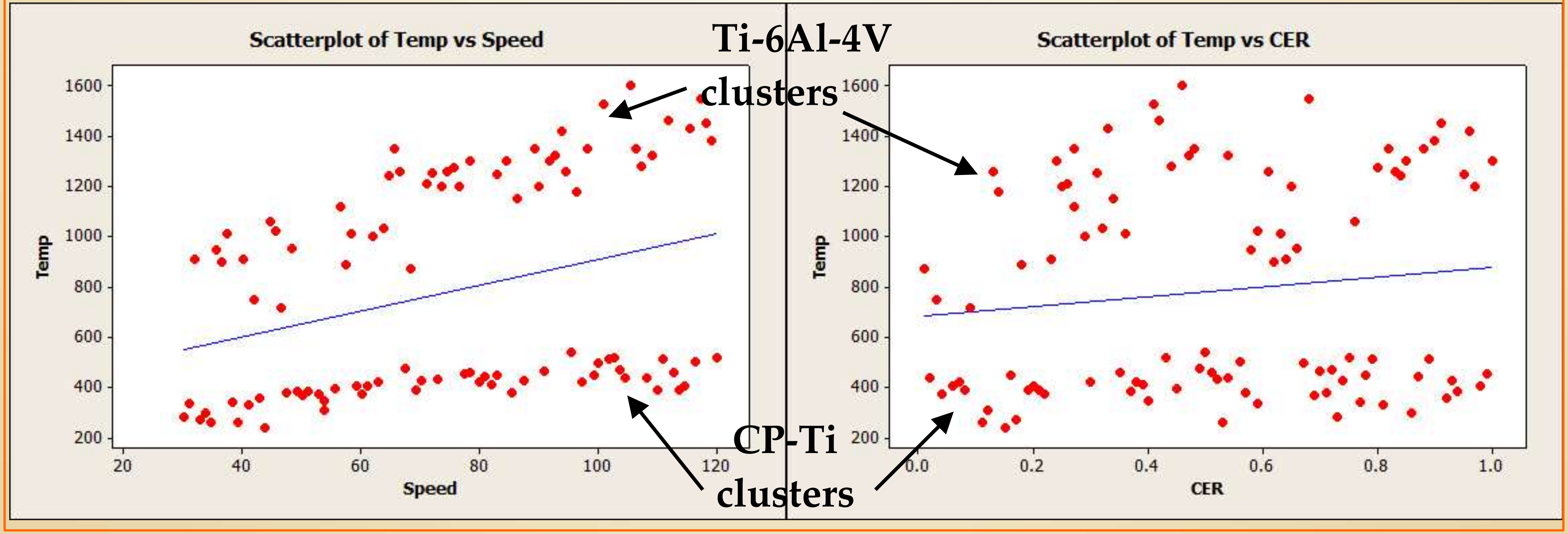




4. Characterization of Factors



1. **Alloy type is the most important factor**
2. **Regression analysis**
3. **DOE study for characterizing feed-speed dependence**
4. **DOE study for characterizing DoC dependence**



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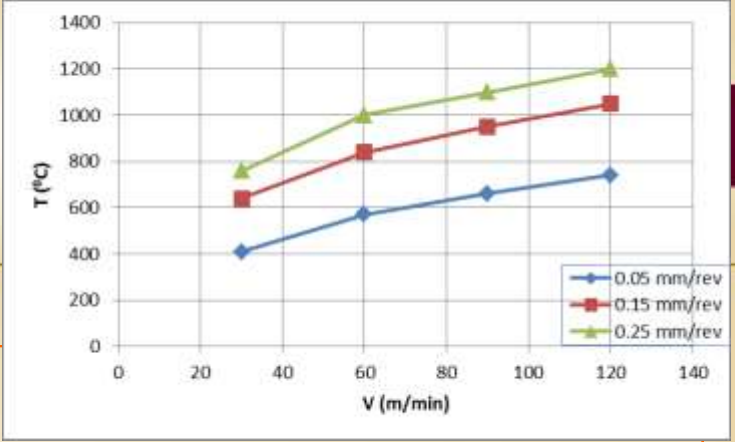


1. Alloy type is the most important factor
2. Regression analysis
3. DOE study for characterizing feed-speed dependence
4. DOE study for characterizing DoC dependence

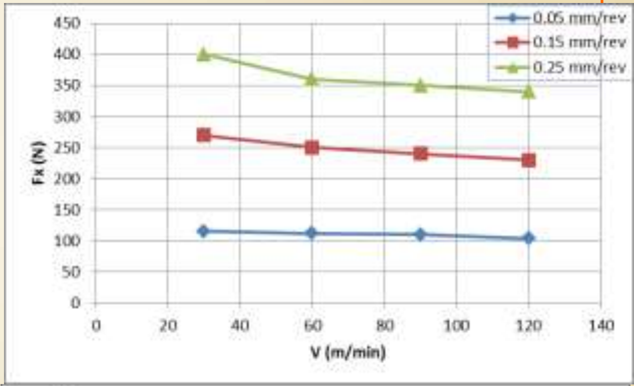
Regression Analysis: Temp versus 12 Input Variables

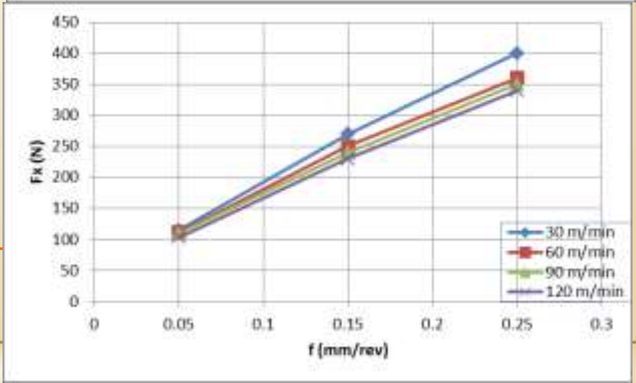
The regression equation is:

Temp = - 132 + 5.4 Cool + 17.8 Cool_Loc + 0.026 Cool_Temp + 159 CER + 4.08 Speed
+ 14.4 DoC + 771 Feed - 0.00047 Cool_HT + 0.293 WP_Temp - 0.51 Rake
- 1.02 Relief + 783 Alloy

Predictor	Coef	SE Coef	T	P	VIF
Constant	-131.58	64.67	-2.03	0.045	
Cool	5.39	19.70	0.27	0.785	1.219
Cool_Loc	17.78	20.58	0.86	0.390	1.328
Cool_Temp	0.0259	0.2378	0.11	0.913	1.137
CER	159.47	31.76	5.02	0.000	1.029
Speed	4.0781	0.3699	11.03	0.000	1.195
DoC	14.41	13.90	1.04	0.303	1.277
Feed	770.5	158.6	4.86	0.000	1.087
Cool_HT	-0.000472	0.001912	-0.25	0.805	1.148
WP_Temp	0.2927	0.2421	1.21	0.230	1.177
Rake	-0.514	1.298	-0.40	0.693	1.137
Relief	-1.022	3.230	-0.32	0.752	1.106
Alloy	783.32	19.16	40.89	0.000	1.151

S = 88.3300 R-Sq = 96.2% R-Sq(adj) = 95.7%





RECAP

- VTW & M-Ratio
- Relationships with MRR
- Mapping Wear Mechanisms
- DOE-HPC Project

Scrap?

Thank you!

Questions / Comments