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Milling titanium alloys with PCD

An Element Six webinar

Developing titanium alloy finish machining techniques using Polycrystalline Diamond (PCD)

Dr Thomas Childerhouse

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Titanium

2 bn metric tons:
Estimated steel production in 2022[1]

9.5 mn metric tons:
Estimated titanium production in 2022[2]

1 Source: *Topic: Steel industry worldwide*. [online] Statista. Available at: https://www.statista.com/topics/1149/steel-industry/#topicOverview.
2 Source: Statista. (n.d.). *Titanium production worldwide by country 2020*. [online] Available at: https://www.statista.com/statistics/759972/mine-production-titanium-minerals-worldwide-by-country/.

Challenges - Why is it difficult to machine titanium alloys?

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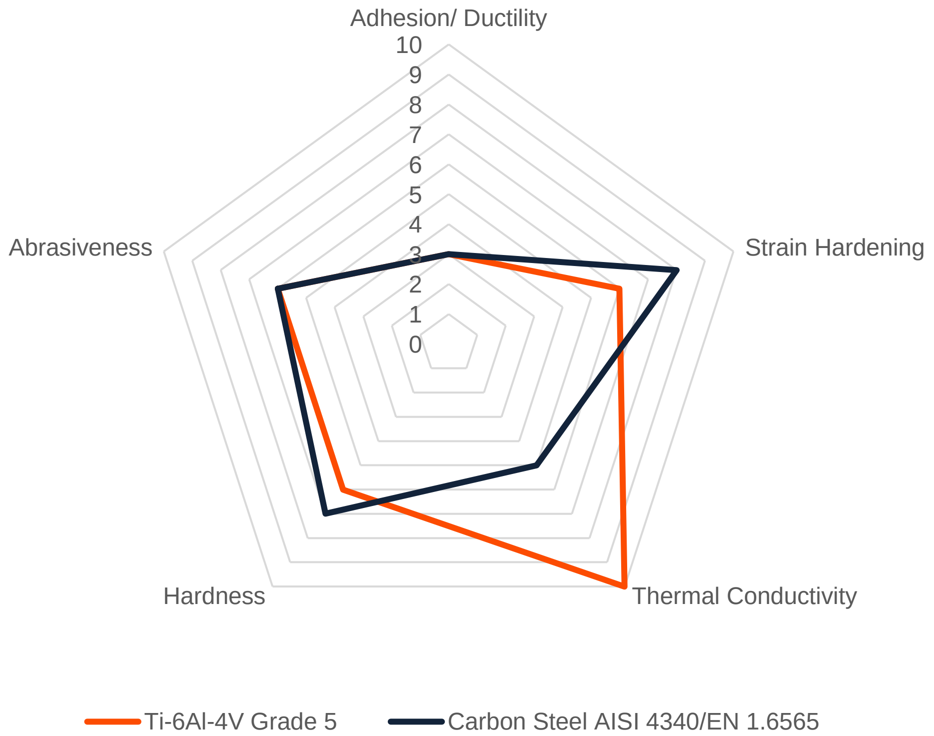
Titanium's machinability is negatively influenced by its:

- Low thermal conductivity
  - 80% lower than carbon steel
  - 50% lower than stainless steel
- Strain hardening matrix
- Hard α phases

Low tool life and poor productivity are typical Ti-alloy machining processes

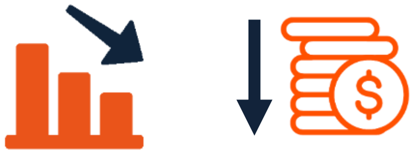


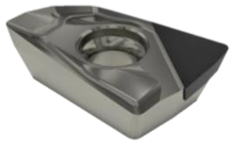
High number = tougher to machine

Source: Jan-Eric Ståhl, Mats Andersson, Volodymyr Bushlya, Jinming Zhou, Andersson, C., Bengt Högrelius, Staffan Gunnarsson, Fredrik Schultheiss and Seco Tools AB (2012). *Metal cutting : theories and models*. Division Of Production And Materials Engineering, Lund University, Lund, Sweden: Lund University Press.

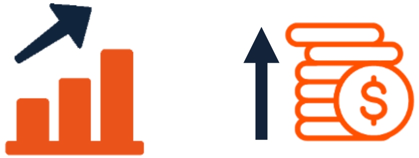
Challenges – Tool selection

WC-Co
Tungsten Carbide Cobalt





PCD
Polycrystalline Diamond



Tool selection still not clear cut

www.secotools.com. (n.d.). *CCGT09T3005-F1 TS2050* | *Seco Tools*. [online] Available at: https://www.secotools.com/article/p_03280810?pf=true [Accessed 30 Oct. 2023].

PCD Ti-Milling and Tool Wear

Implications of PCD grade and cutting parameter selection on tool degradation mechanisms during milling of titanium alloys

Dr Thomas Childerhouse

This work has been published elsewhere:

Childerhouse, T.; M'Saoubi, R.; Franca, L.F.P.; Crawforth, P.; Jackson, M. Machining Performance and Wear Behaviour of Polycrystalline Diamond and Coated Carbide Tools during Milling of Titanium Alloy Ti-54M. *Wear* **2023**, 523, 204791.

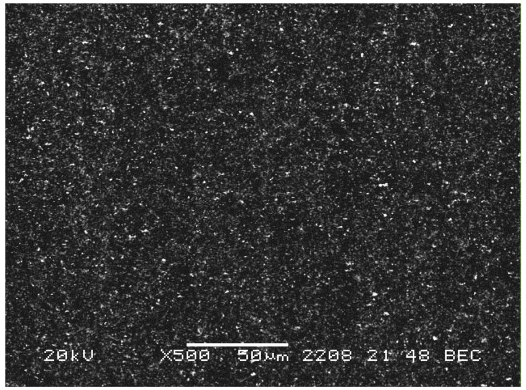
Study aims

- What is the influence of PCD grain size on wear characteristics and tool life during finish milling of titanium alloys?
- How are these wear characteristics influenced by cutting conditions/parameters?
- What are the implications of high speed PCD finishing on the surface integrity of titanium alloys?

Element Six PCD grades tested

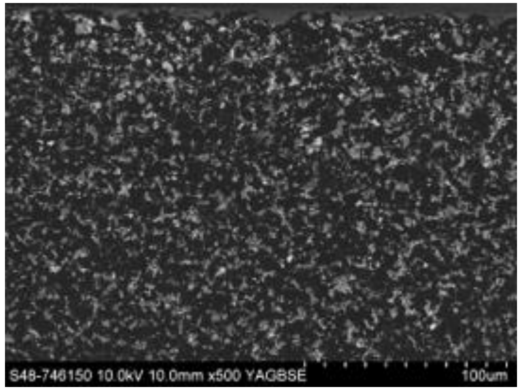
CMX850

- Diamond grain size: Sub-micron
- Co binder content ratio: >15 wt. %



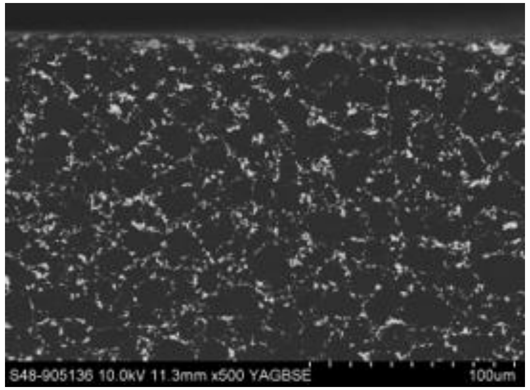
CTB010

- Diamond grain size: 10 µm (avg.)
- Co binder content ratio: 10 to 13 wt. %



CTM302

- Diamond grain size: Multimodal 2 to 30 µm
- Co binder content ratio: 10 to 13 wt. %



Increasing grain size →

Increasing thermal conductivity →

Decreasing toughness & rupture strength →

PCD Tool format

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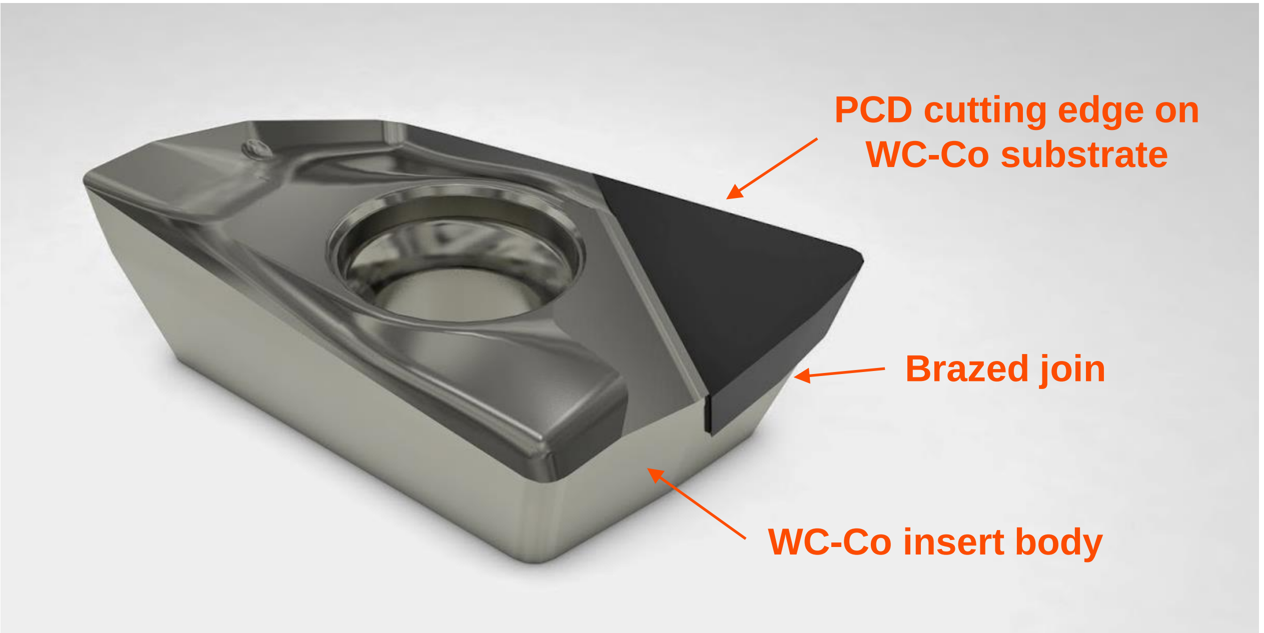


PCD tipped WC-Co cutting insert

Commercially available tool, mechanically ground and optimised for milling aluminium alloys

Timetal® Ti-54M workpiece

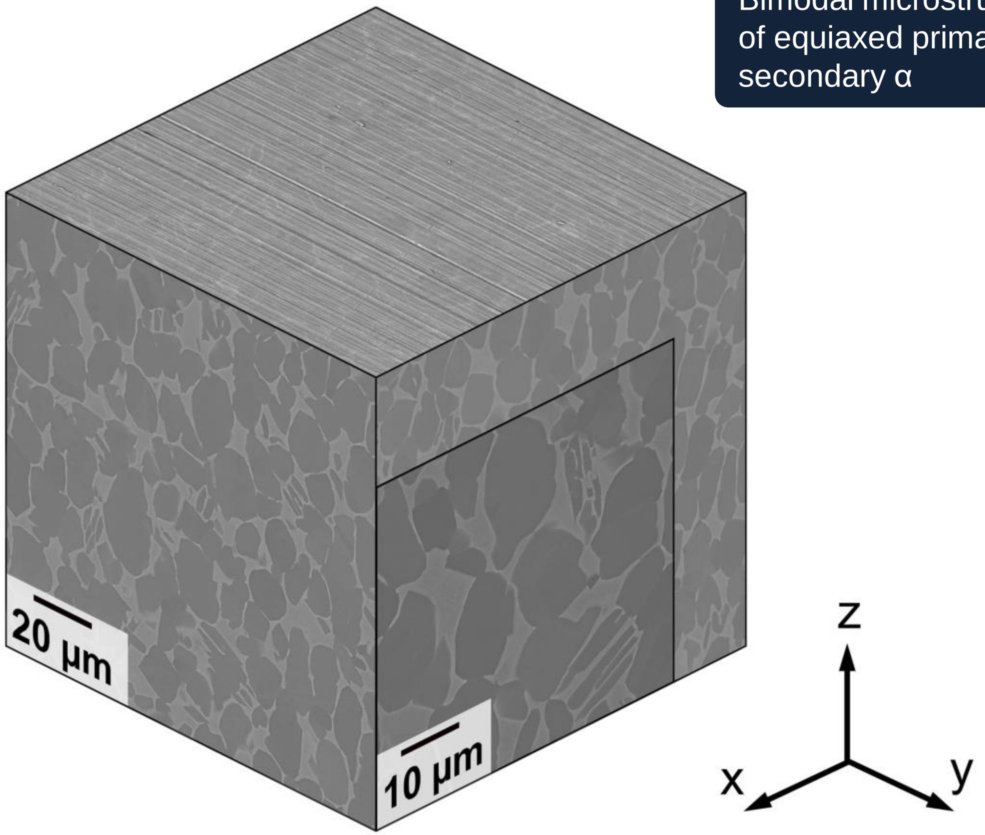
Ti-54M:

- Improved machinability than Ti-6Al-4V
- Similar mechanical properties

Al	V	Mo	C	Fe	O	N	Ti
5.18	3.99	0.78	6E-4	0.45	0.16	3E-3	Bal.

Chemical composition of the Ti-54M workpiece material. Values provided in wt. %.

Bimodal microstructure consisting of equiaxed primary α + colony secondary α



Supplied by TIMET in the as-forged, mill annealed condition

Square shoulder milling configuration

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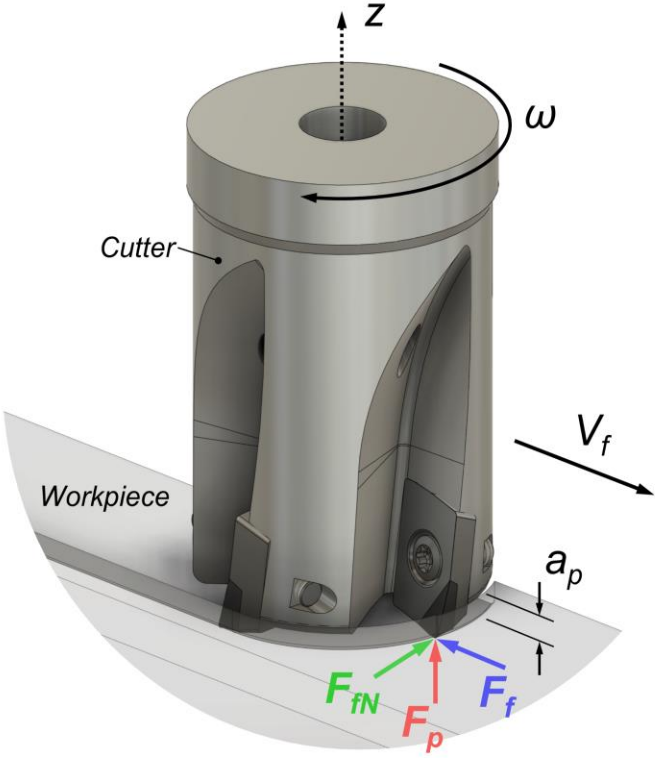
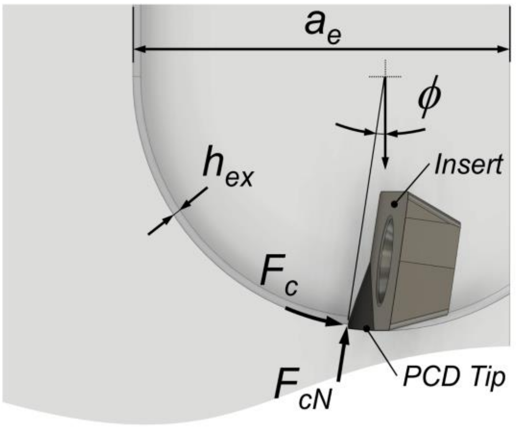
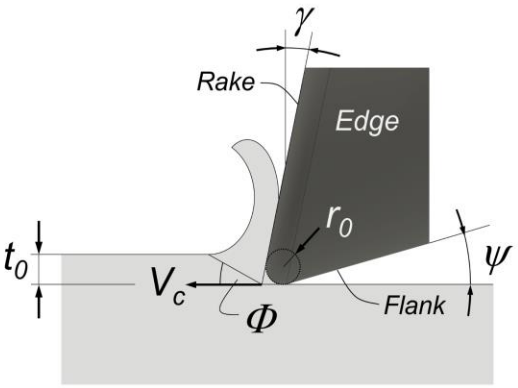






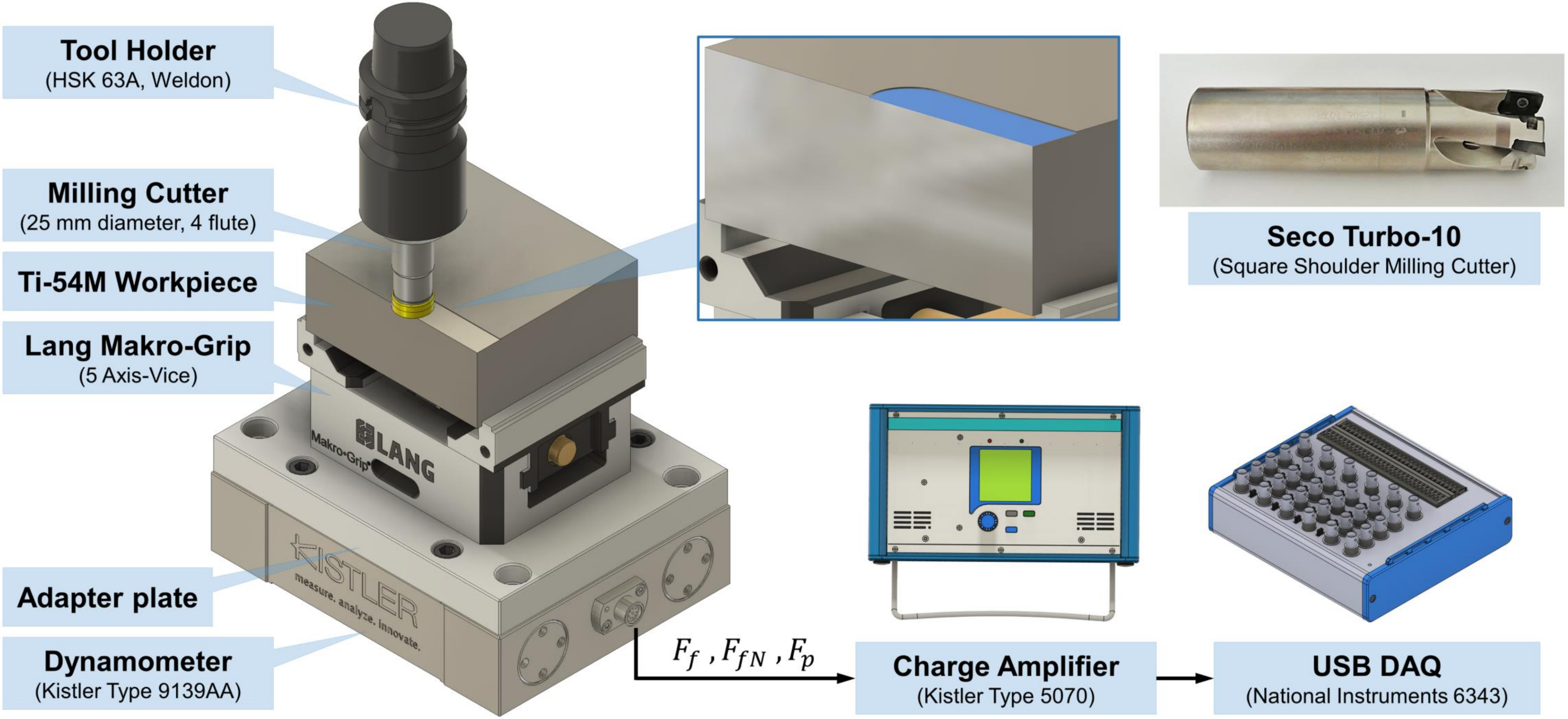
Radial DoC, a_e [mm]	Axial DoC, a_p [mm]	Edge rad, r [µm]	Rake angle, Y [°]	Clear. angle, ψ [°]	Cutter dia. [mm]	Cutter offset [mm]
19.00	0.50	<10	+23	7	25.00	3.00

V_c (m/min)	200	300	400	450	500	600
f_z (µm/tooth)	30	20	15	13.4	12	10

Maintaining a material removal rate of 0.73 cm^3/min

*Typical cutting parameters for WC-Co tooling: V_c ~ 60-80 m/min, f_z ~ 80-100 µm.

Test set up


Tool Holder
(HSK 63A, Weldon)
Milling Cutter
(25 mm diameter, 4 flute)
Ti-54M Workpiece
Lang Makro-Grip
(5 Axis-Vice)
Adapter plate
Dynamometer
(Kistler Type 9139AA)
F_f , F_{fN} , F_p
Seco Turbo-10
(Square Shoulder Milling Cutter)
Charge Amplifier
(Kistler Type 5070)
USB DAQ
(National Instruments 6343)

Cutting parameter selection

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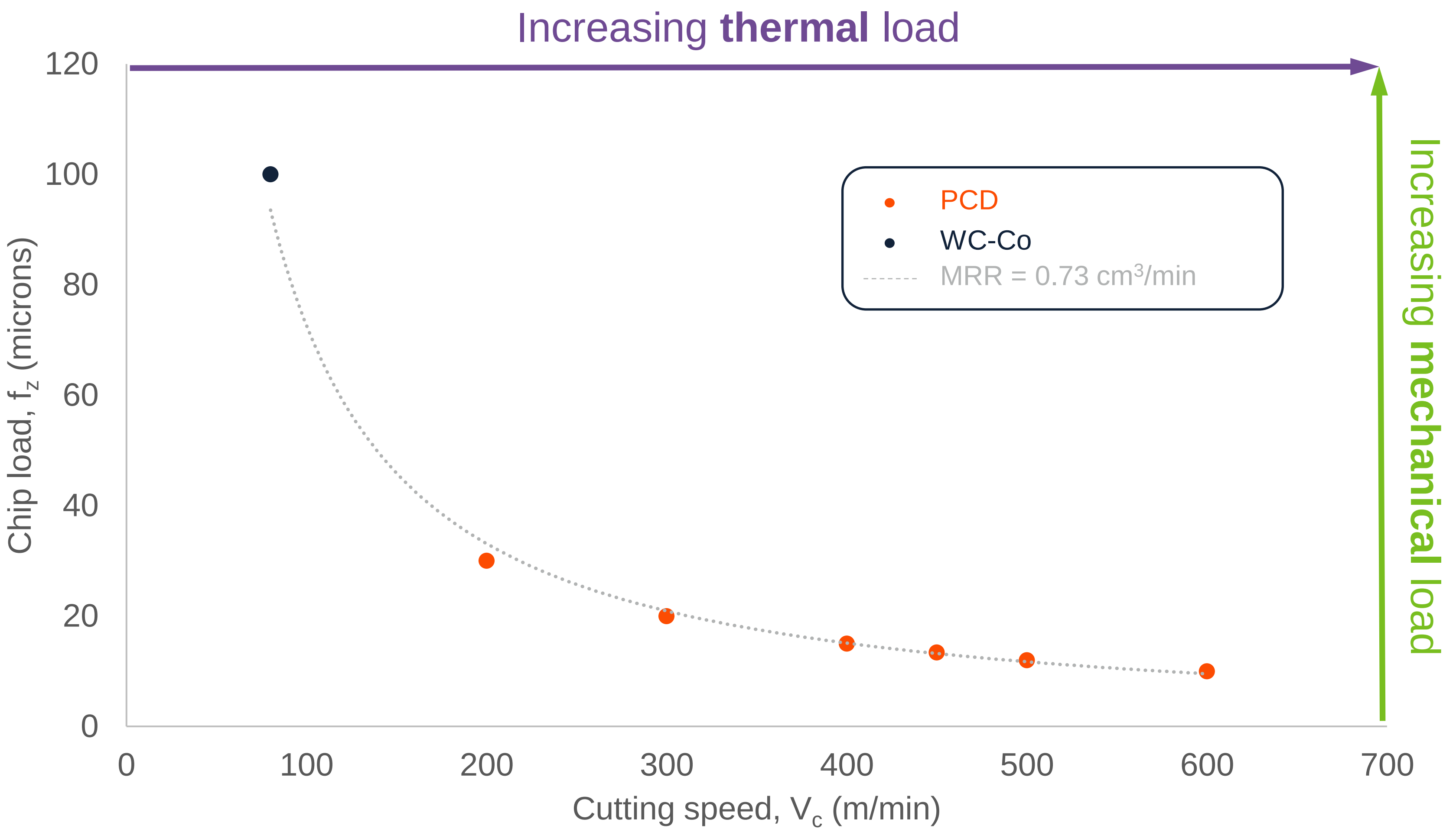


Maintaining consistent material removal rates while transitioning from mechanical to thermal loads

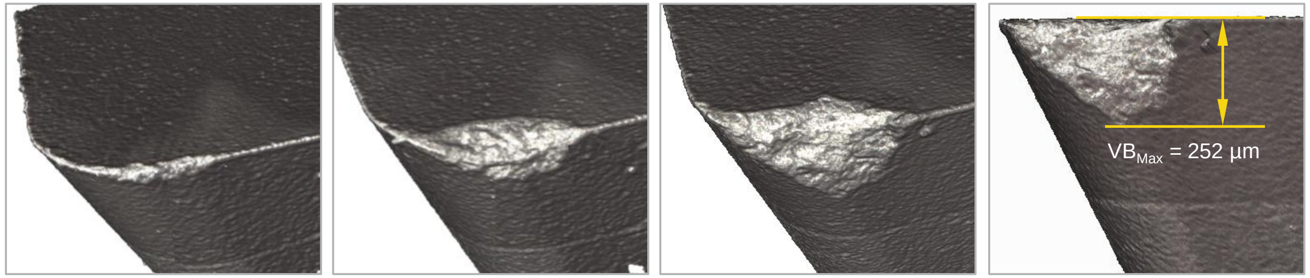
Results: Tool life

Comparing three grades of PCD

Results: Tool life

CTM302 analysis

CTM302 (500 m/min, 12.0 µm/tooth)



(i) t_c = 1.86 min (ii) t_c = 7.47 min (iii) t_c = 9.34 min (iii) t_c = 9.34 min

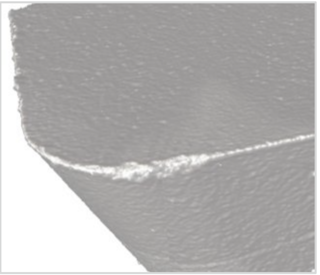
CTM302 2-30 µm (avg.) grain size:

- Tool life* = **7 min.**
- Similar wear scar observed to the CTB010 indicating fracture dominated wear.
- Largest grain size has resulted in the shortest tool life.

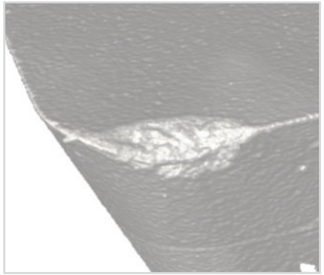
Results: Tool life

CTB010 analysis

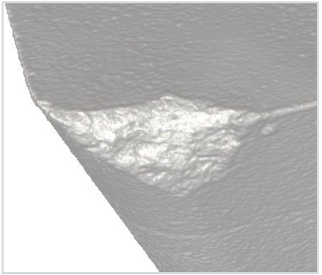
CTM302 (500 m/min, 12.0 µm/tooth)



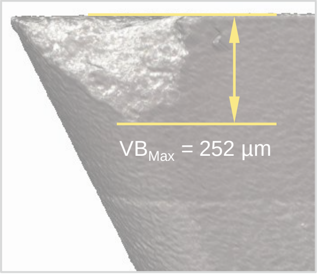
(i) t_c = 1.86 min



(ii) t_c = 7.47 min



(iii) t_c = 9.34 min



(iii) t_c = 9.34 min

CTM302 2-30 µm (avg.) grain size:

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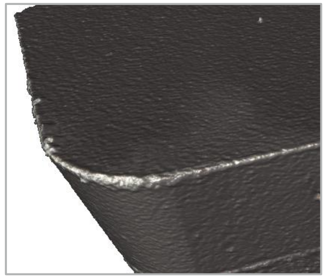
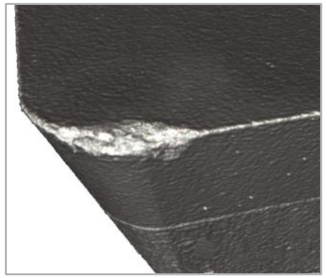
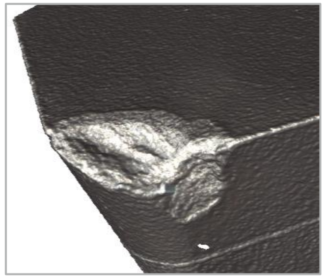
CTB010 (500 m/min, 12.0 µm/tooth)



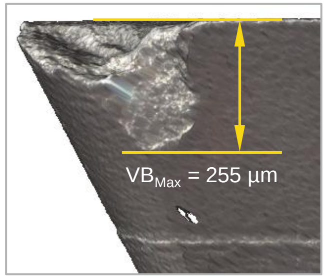
(i) t_c = 1.86 min



(ii) t_c = 7.47 min



(iii) t_c = 13.1 min



(iii) t_c = 13.1 min

CTB010 10 µm (avg.) grain size:

- Tool life* = **12 min.**
- Fracture/chipping to cutting edge is the dominant wear mechanism.
- Larger grain size and the lower fracture toughness contribute to this behaviour.

Results: Tool life

CMX850 analysis

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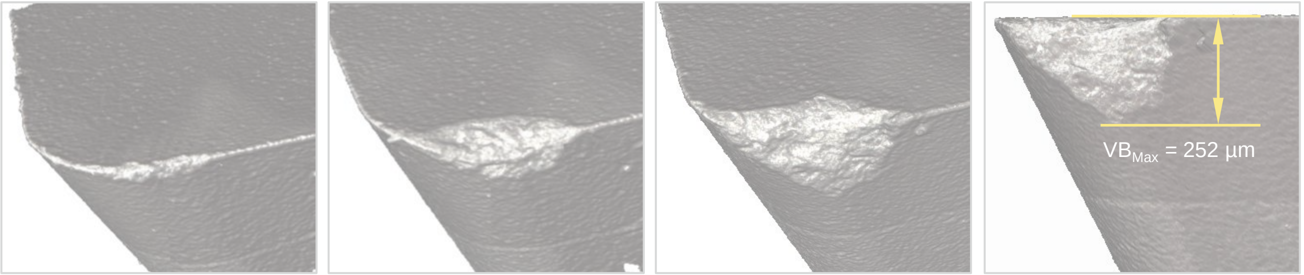
CTM302 (500 m/min, 12.0 µm/tooth)



(i) t_c = 1.86 min (ii) t_c = 7.47 min (iii) t_c = 9.34 min (iii) t_c = 9.34 min

CTM302 2-30 µm (avg.) grain size:

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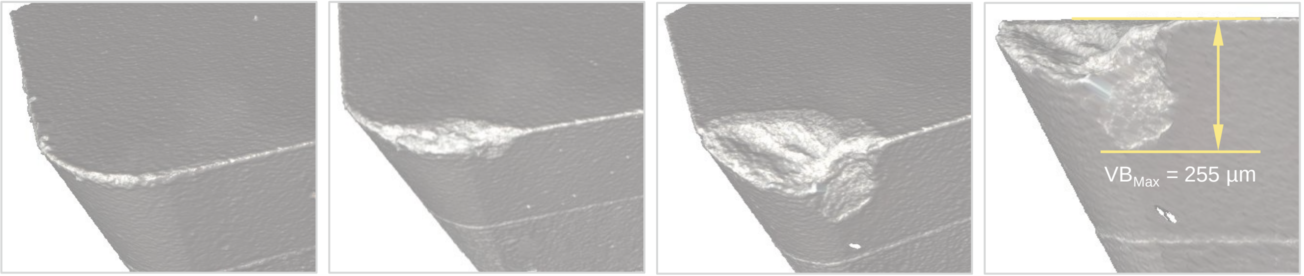
CTB010 (500 m/min, 12.0 µm/tooth)

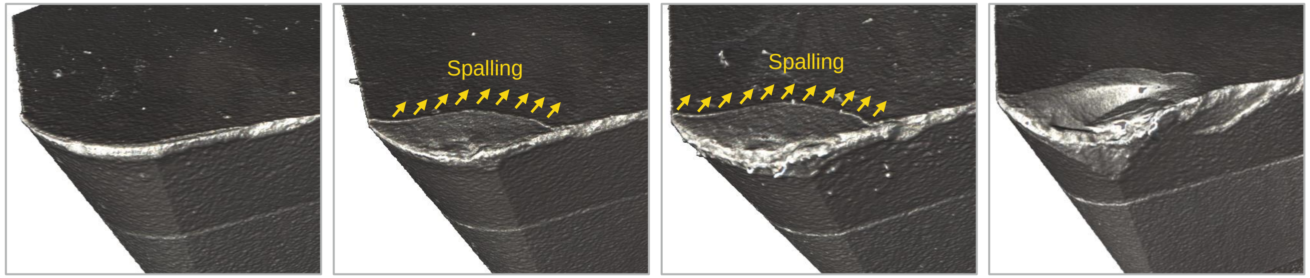


(i) t_c = 1.86 min (ii) t_c = 7.47 min (iii) t_c = 13.1 min (iii) t_c = 13.1 min

CTB010 10 µm (avg.) grain size:

- Tool life* = **12 min.**
- Fracture/chipping to cutting edge is the dominant wear mechanism.
- Larger grain size and the lower fracture toughness contribute to this behaviour.

CMX850 (450 m/min, 13.4 µm/tooth)



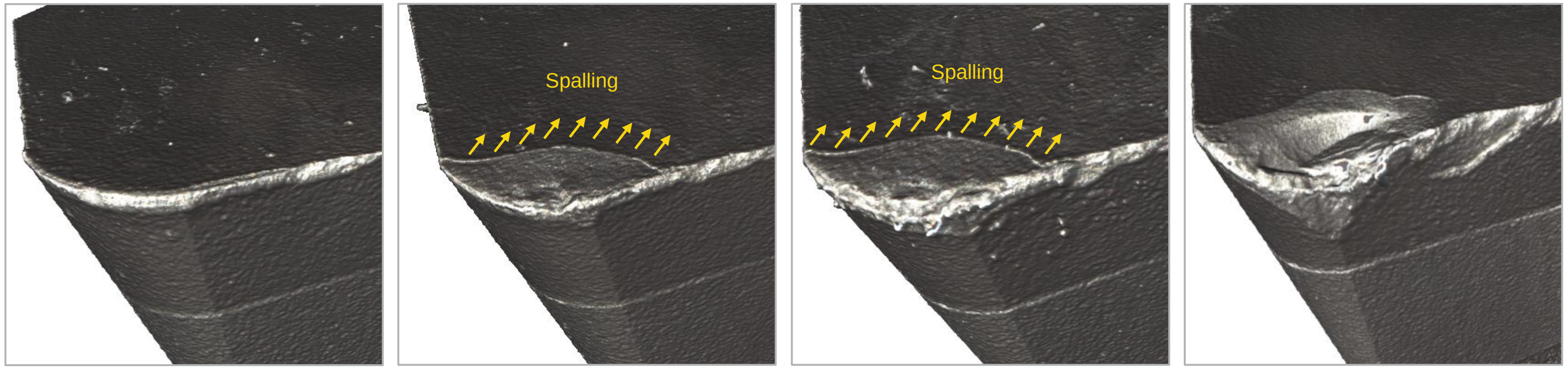
(i) t_c = 5.61 min (ii) t_c = 11.2 min (iii) t_c = 16.8 min (iv) t_c = 24.3 min

CMX850 Sub-micron grain size:

- Tool life* = **24 min.**
- Small grain size critical for fracture resistance.
- Adhesive/abrasive (spalling) driven wear mechanism.

Summary

CMX850 (450 m/min, 13.4 μm/tooth)



(i) t_c = 5.61 min (ii) t_c = 11.2 min (iii) t_c = 16.8 min (iv) t_c = 24.3 min

Grade	Grain size	Chip resistance	Abrasion resistance
CMX850	0.85-1 μm	■■■■■■■■■■	■■■■■■■□□□
CTX002	2 μm	■■■■■■■■■□	■■■■■□□□□□
CTB004	4 μm	■■■■■■■■■□	■■■■■■■□□□
CTB010	10 μm	■■■■■■■■□□	■■■■■■■■□□
CTH025	25 μm	■■■■■■■□□□	■■■■■■■■■□
CTM302	2-30 μm	■■■■■■■□□□	■■■■■■■■■■

Toughness provided by Element Six CMX850 PCD is critical to prevent tool fracture and extend tool life

Results: Cutting conditions

Influence of cutting conditions on CMX850 performance

Results: Influence of cutting conditions on CMX850 performance

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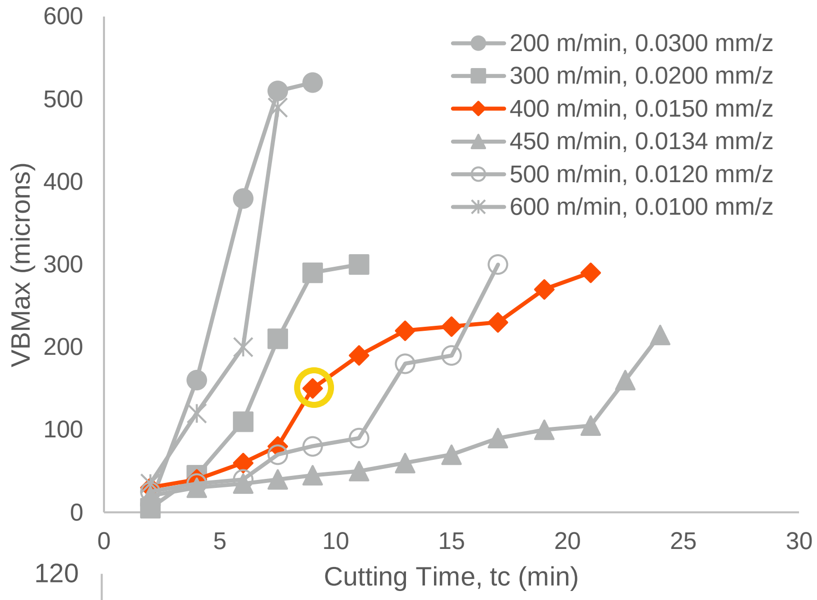
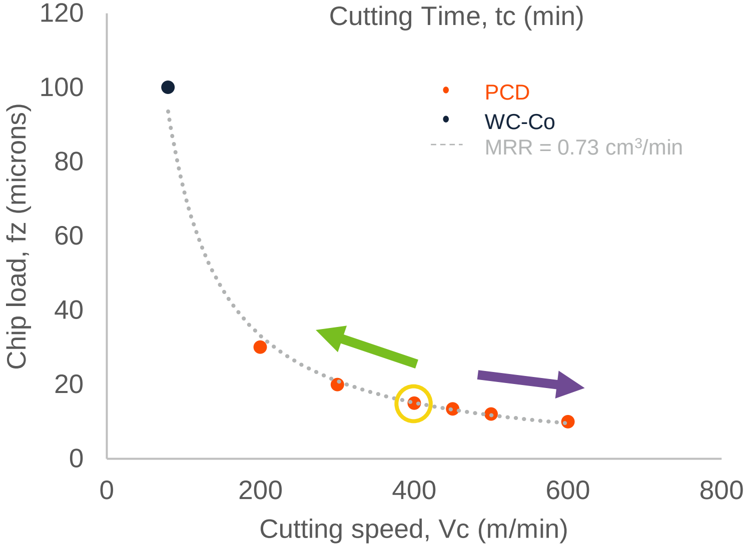
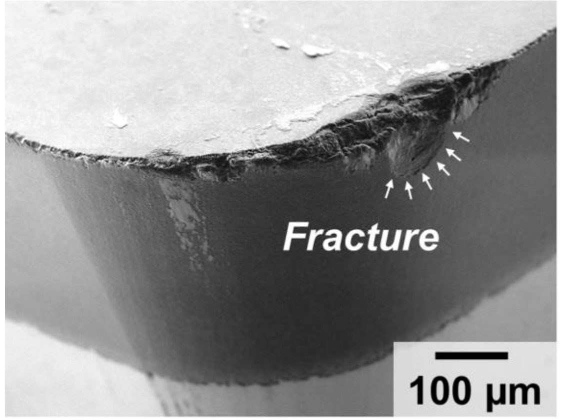
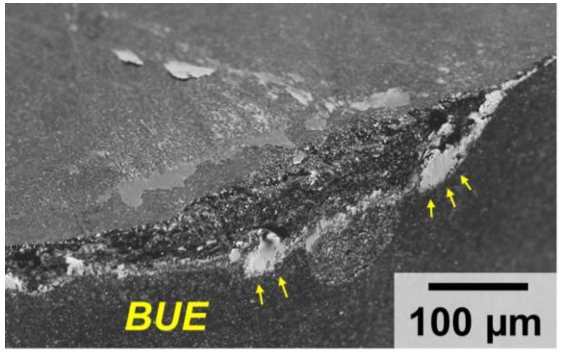
Mechanical load dominated wear mode – Tool life: **9 minutes**





Cutting speed: **400 m/min**
Chip Load: **15.0 µm**





Images reproduced from Childerhouse, T.; M'Saoubi, R.; Franca, L.F.P.; Crawforth, P.; Jackson, M. Machining Performance and Wear Behaviour of Polycrystalline Diamond and Coated Carbide Tools during Milling of Titanium Alloy Ti-54M. *Wear* **2023**, 523, 204791.

Results: Influence of cutting conditions on CMX850 performance

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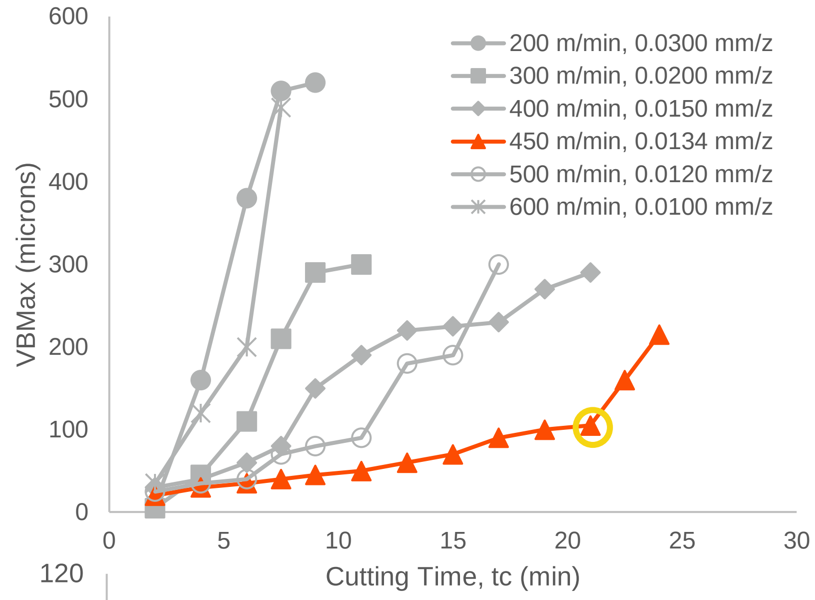
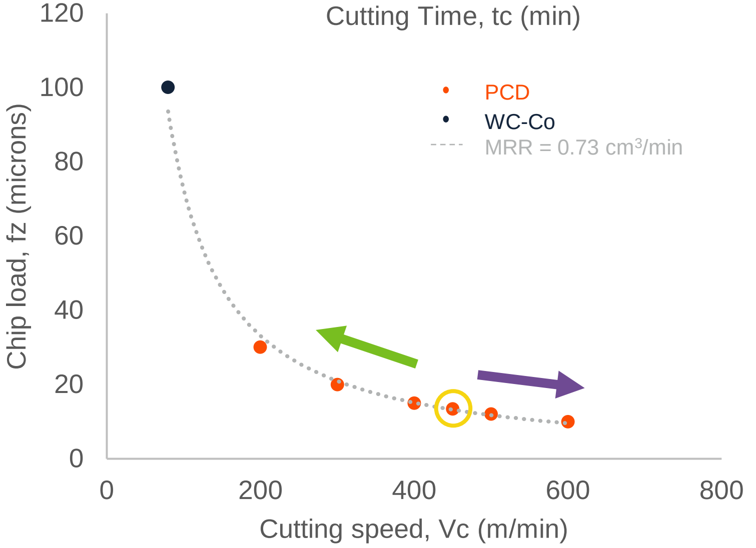
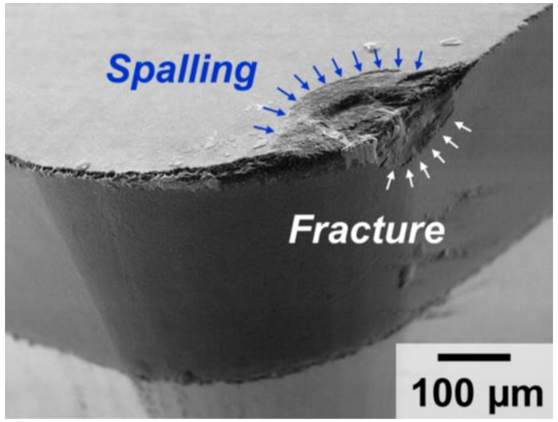
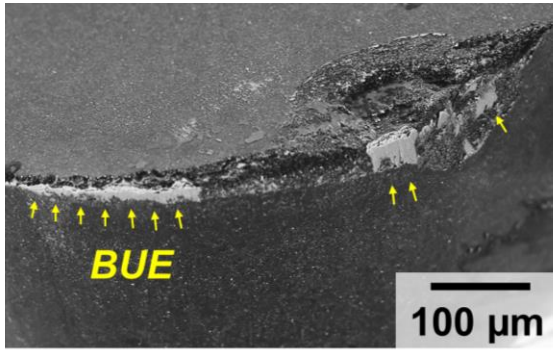
Transitioning between mechanical and thermal loading – Tool life: **21 minutes**





Cutting speed: **450 m/min**
Chip Load: **13.4 µm**





Fracture ← Increasing **Mechanical** Load | Increasing **Thermal** Load → **Spalling**

Images reproduced from Childerhouse, T.; M'Saoubi, R.; Franca, L.F.P.; Crawforth, P.; Jackson, M. Machining Performance and Wear Behaviour of Polycrystalline Diamond and Coated Carbide Tools during Milling of Titanium Alloy Ti-54M. *Wear* **2023**, 523, 204791.

Results: Influence of cutting conditions on CMX850 performance

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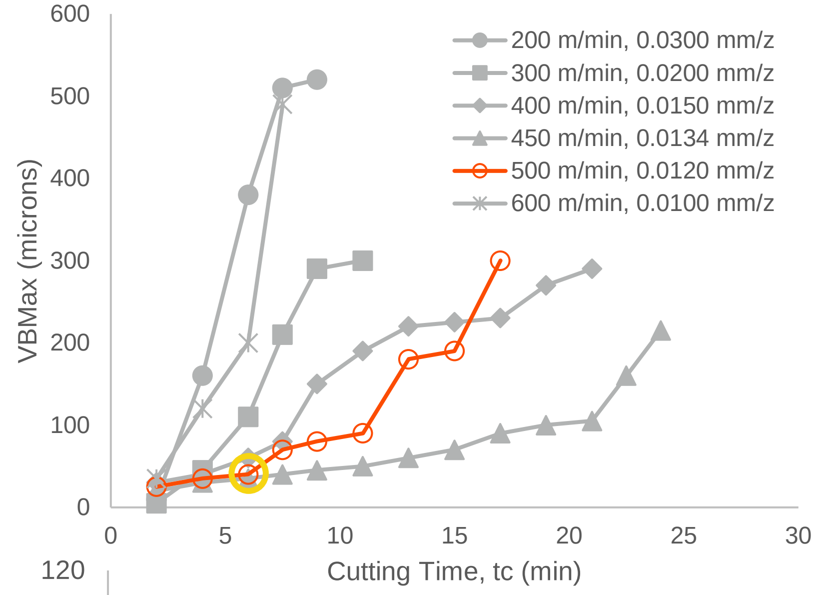
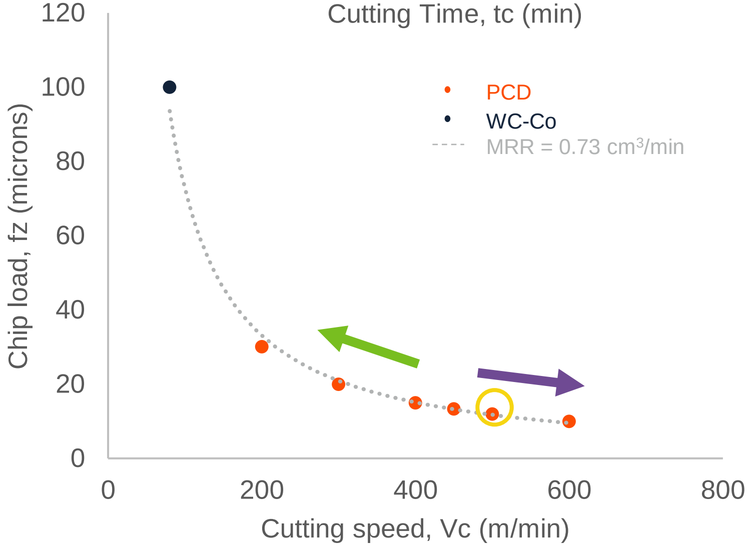
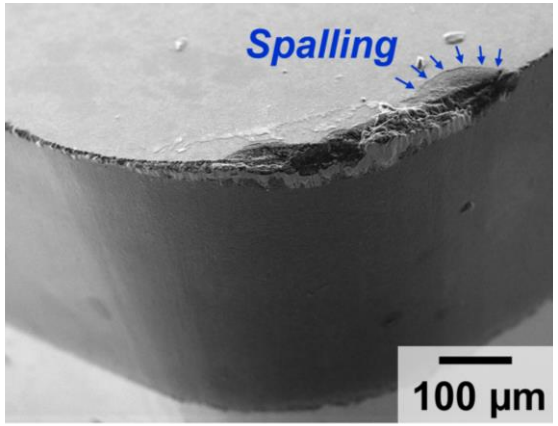
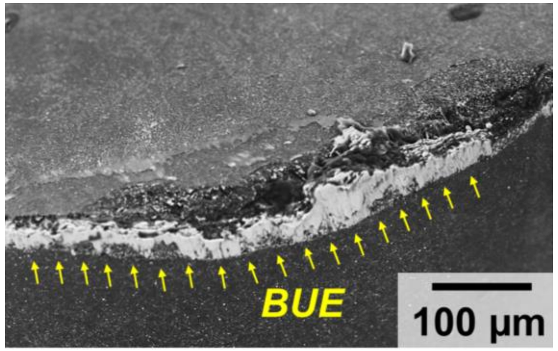
Thermal load dominated wear mode – Tool life: **7 minutes**





Cutting speed: **500 m/min**
Chip Load: **12.0 µm**





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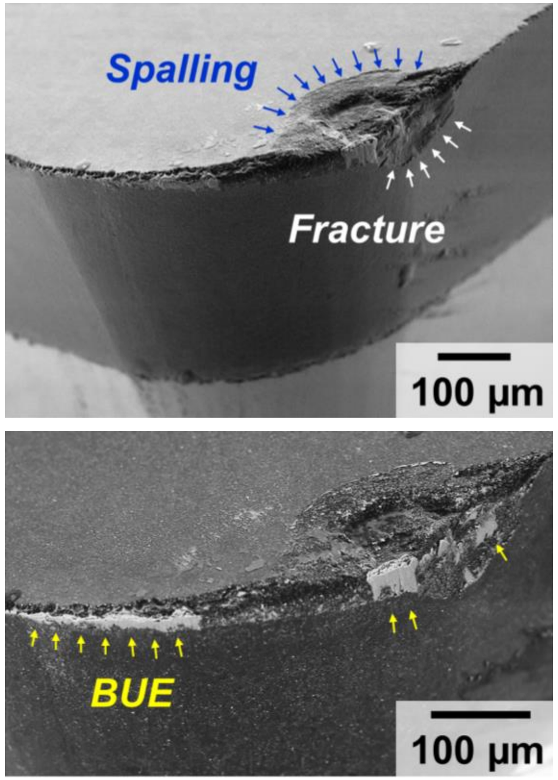
Summary: Influence of cutting conditions on CMX850 performance

Cutting speed: **450 m/min**
Chip Load: **13.4 µm**

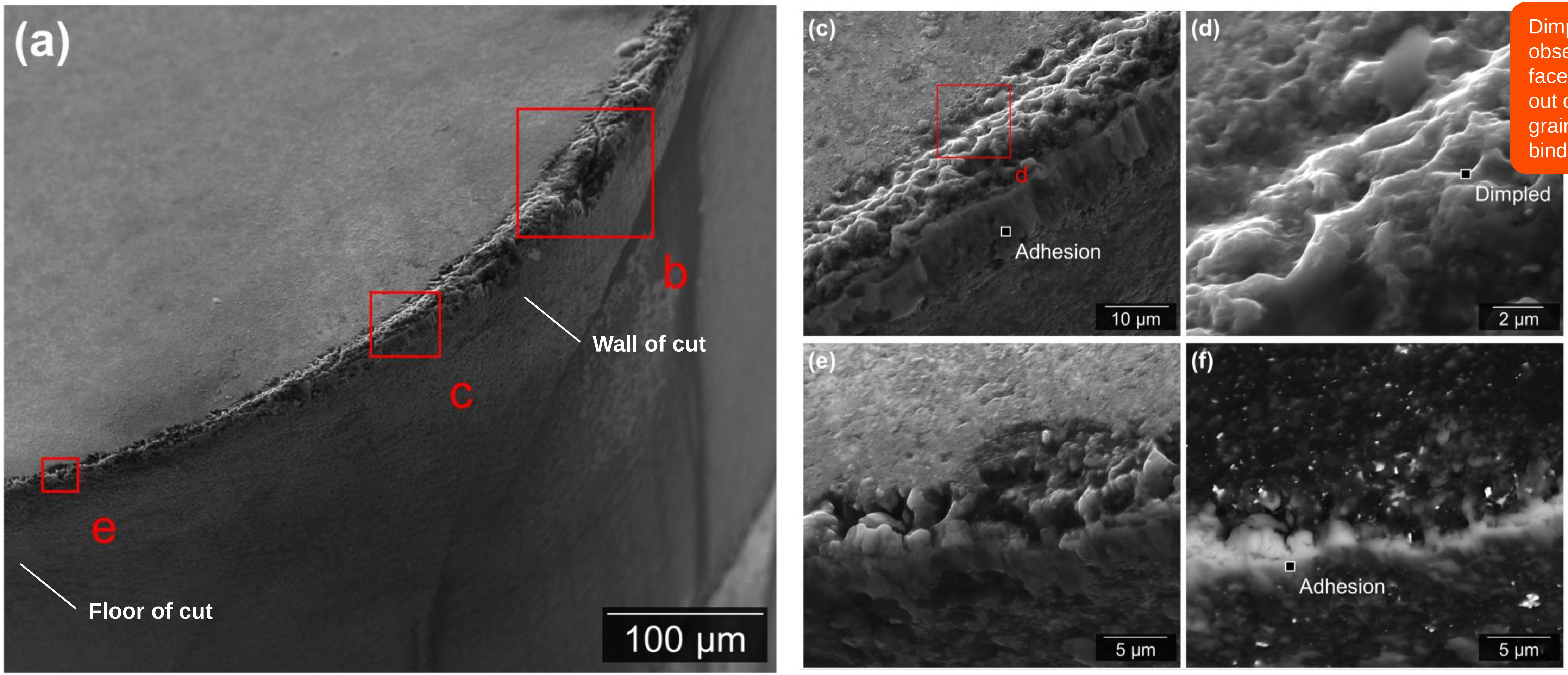
CMX850 – Tool Life: **21 mins**



Tool life optimised at cutting conditions where wear mechanism transitions from fracture to spalling

Images reproduced from Childerhouse, T.; M'Saoubi, R.; Franca, L.F.P.; Crawforth, P.; Jackson, M. Machining Performance and Wear Behaviour of Polycrystalline Diamond and Coated Carbide Tools during Milling of Titanium Alloy Ti-54M. *Wear* **2023**, 523, 204791.

Results: Wear morphology SE analysis



The CMX850 cutting edge when machining at 450 m/min, 0.0134 mm/z following t_c = 3.74 min.

Dimpled wear scar observed at rake face suggests pull-out of diamond grains from Co binder matrix

Results: Cutting force response

Influence of cutting conditions on force response

Results: Cutting force response

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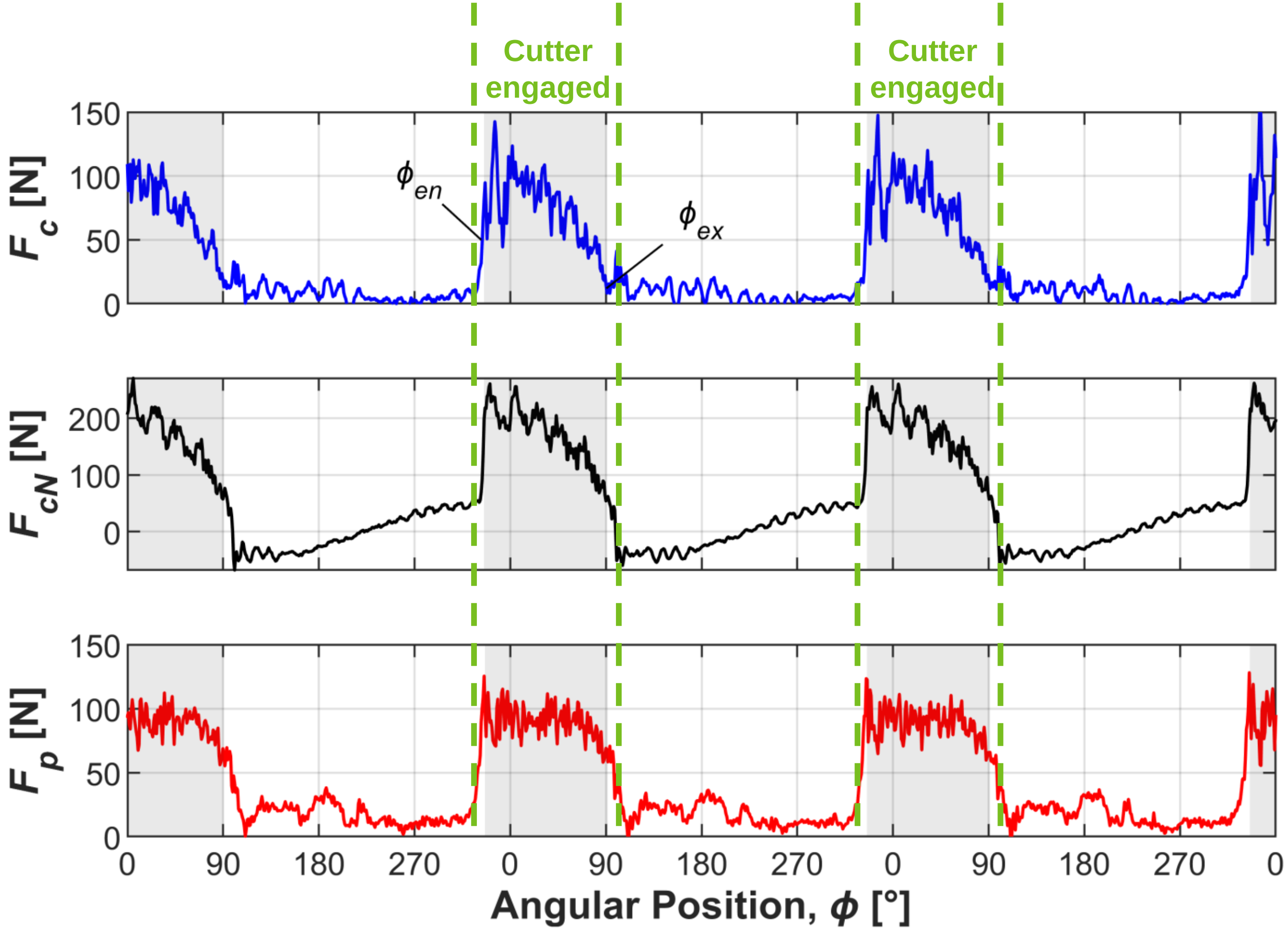

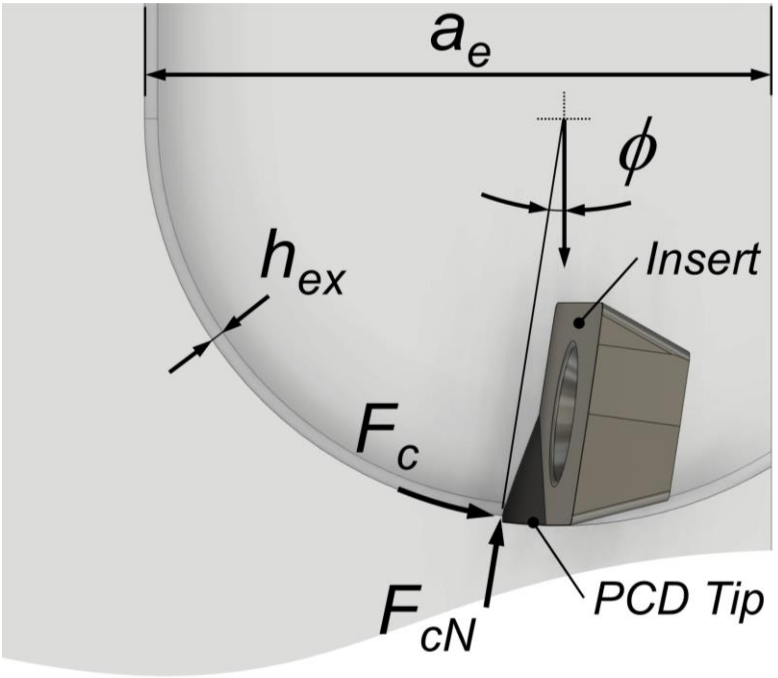

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Results: Cutting force response

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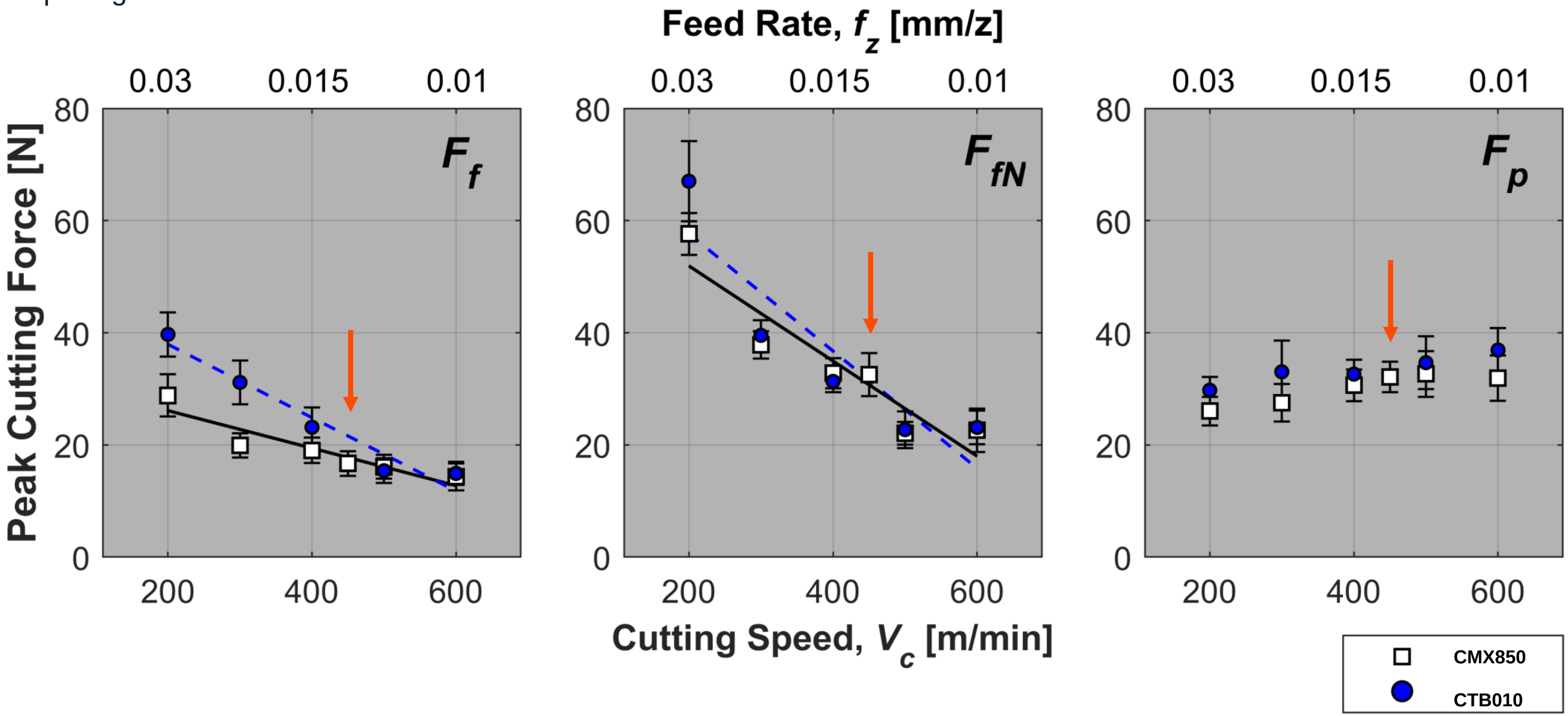
- Fracture to spalling transition



Cutting force response indicates peak forces at which spalling is observed

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Results: Cutting force response

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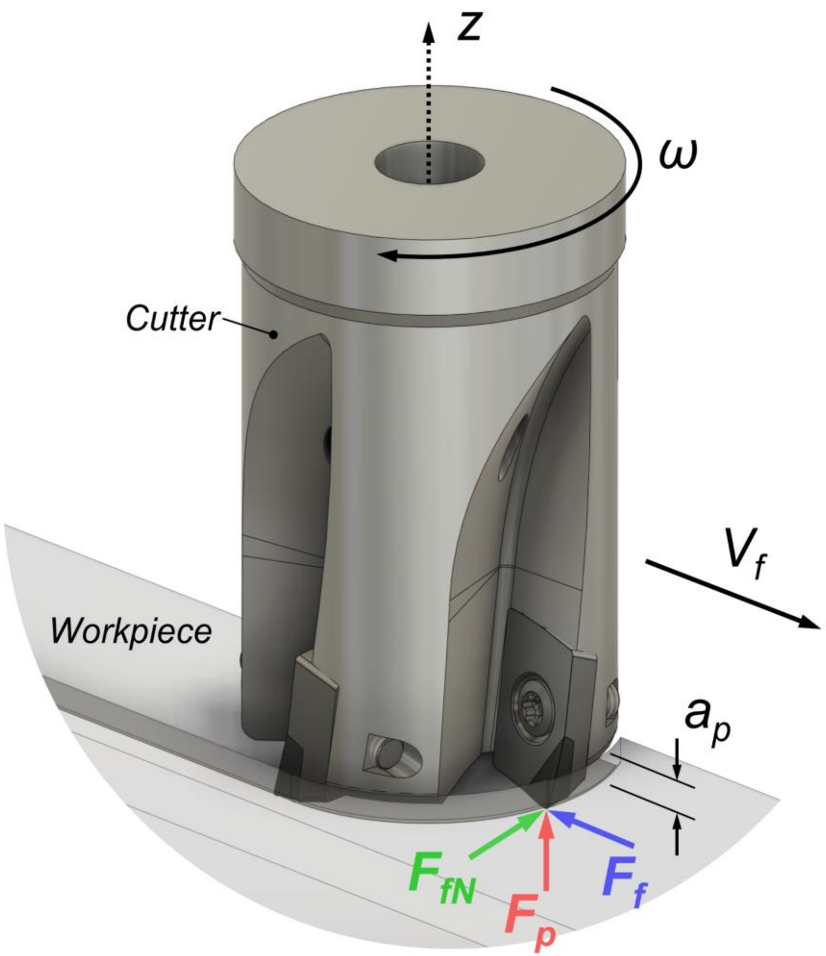
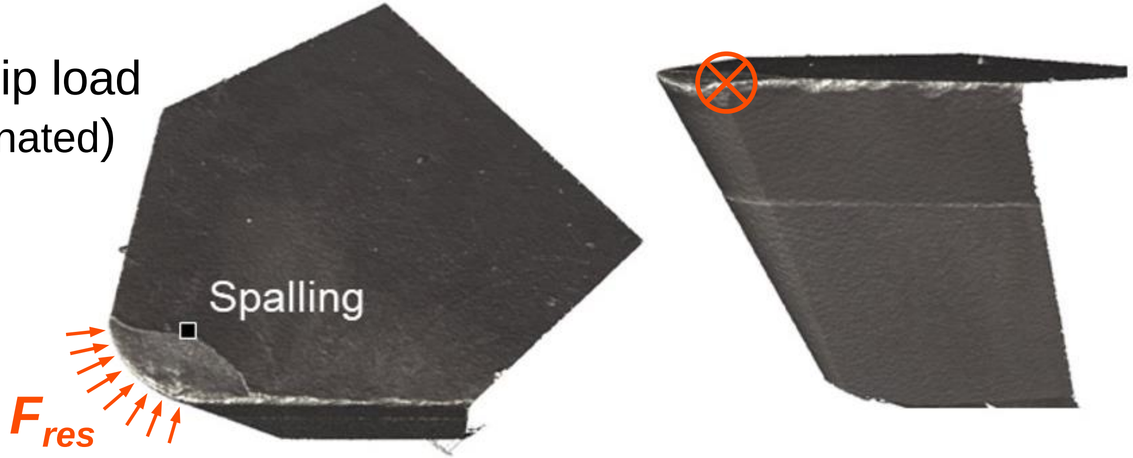
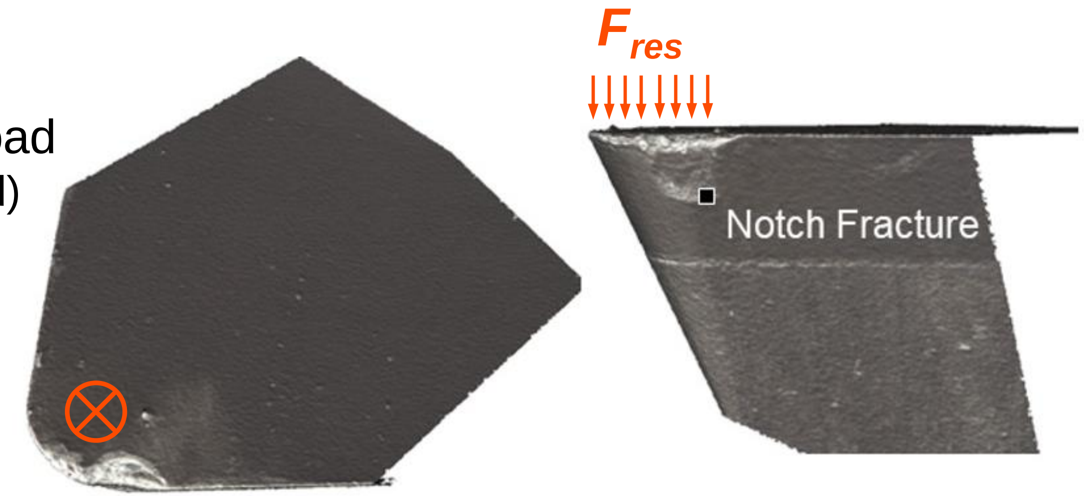


1. Reduced chip load
(spalling dominated)



2. Increased chip load
(fracture dominated)



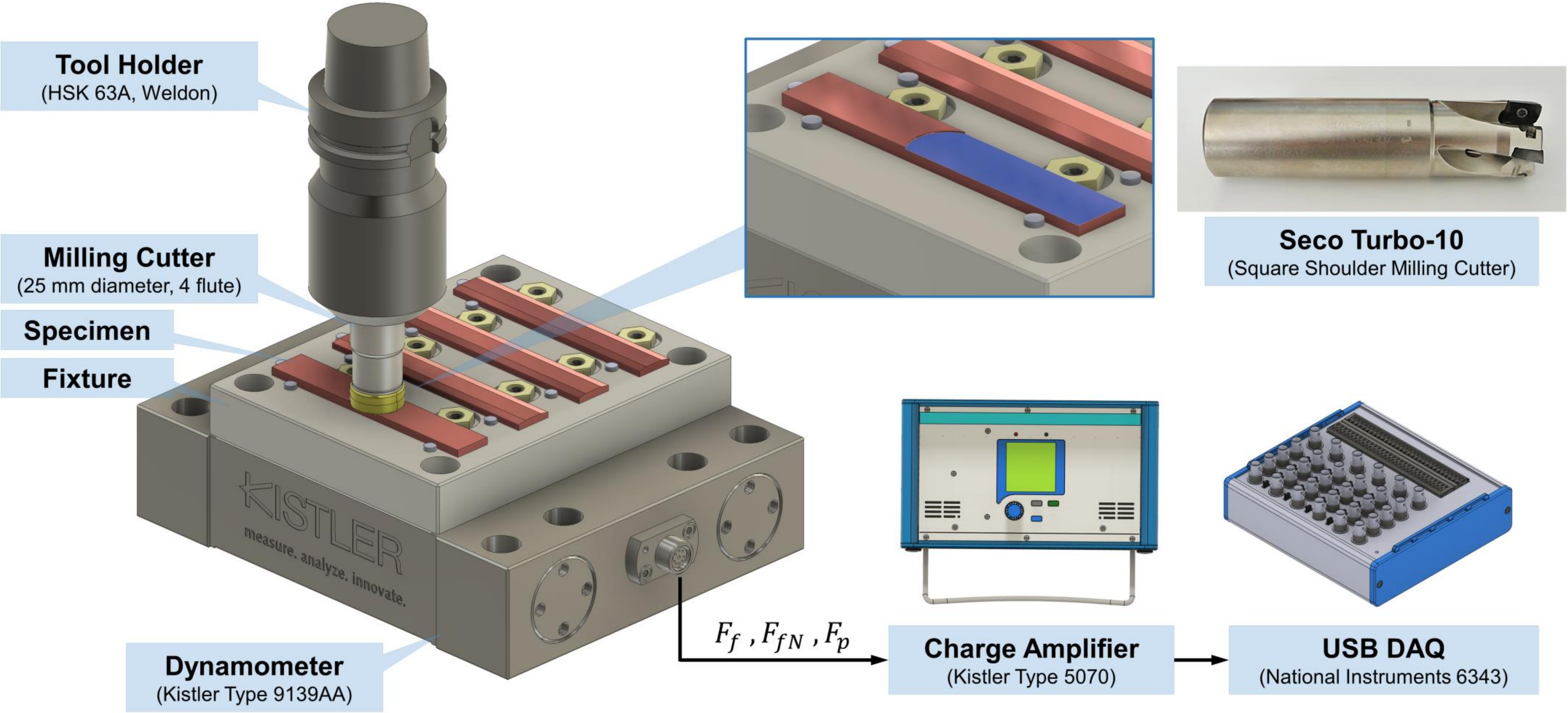
PCD Ti-Milling and Surface Integrity

Implications of PCD cutting tool materials and high speed / low feed machining on the surface integrity of titanium alloys

This work has been published elsewhere:

Childerhouse, T.; M'Saoubi, R.; Franca, L.F.P.; Weston, N.; Jackson, M. The influence of machining induced surface integrity and residual stress on the fatigue performance of Ti-6Al-4V following polycrystalline diamond and coated cemented carbide milling. *International Journal of Fatigue* **2022**, 163, 107054.

Method: Surface generation



Images reproduced from Childerhouse, T.; M'Saoubi, R.; Franca, L.F.P.; Weston, N.; Jackson, M. The influence of machining induced surface integrity and residual stress on the fatigue performance of Ti-6Al-4V following polycrystalline diamond and coated cemented carbide milling. *International Journal of Fatigue* **2022**, 163, 107054.

Cutting parameter selection

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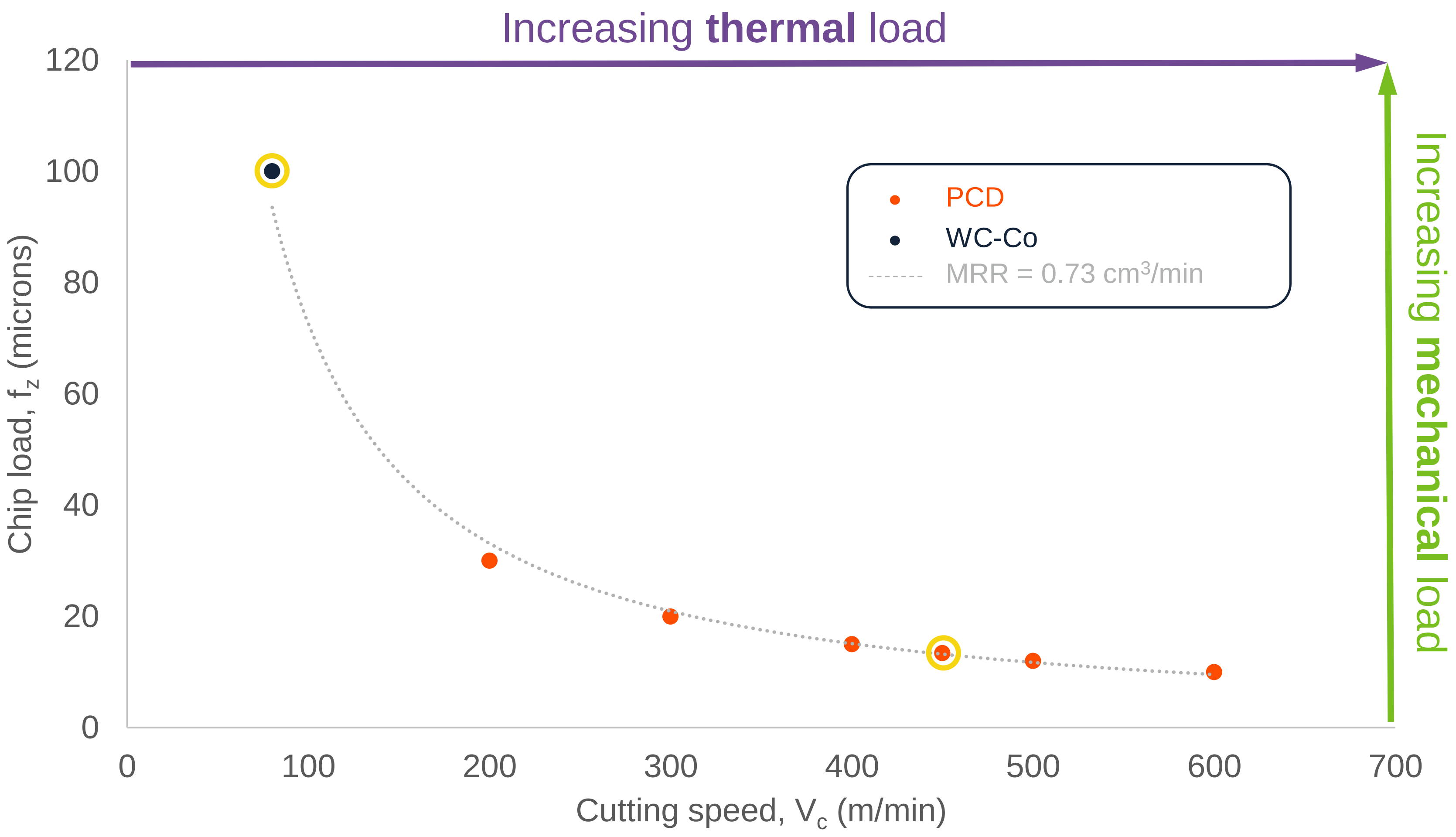
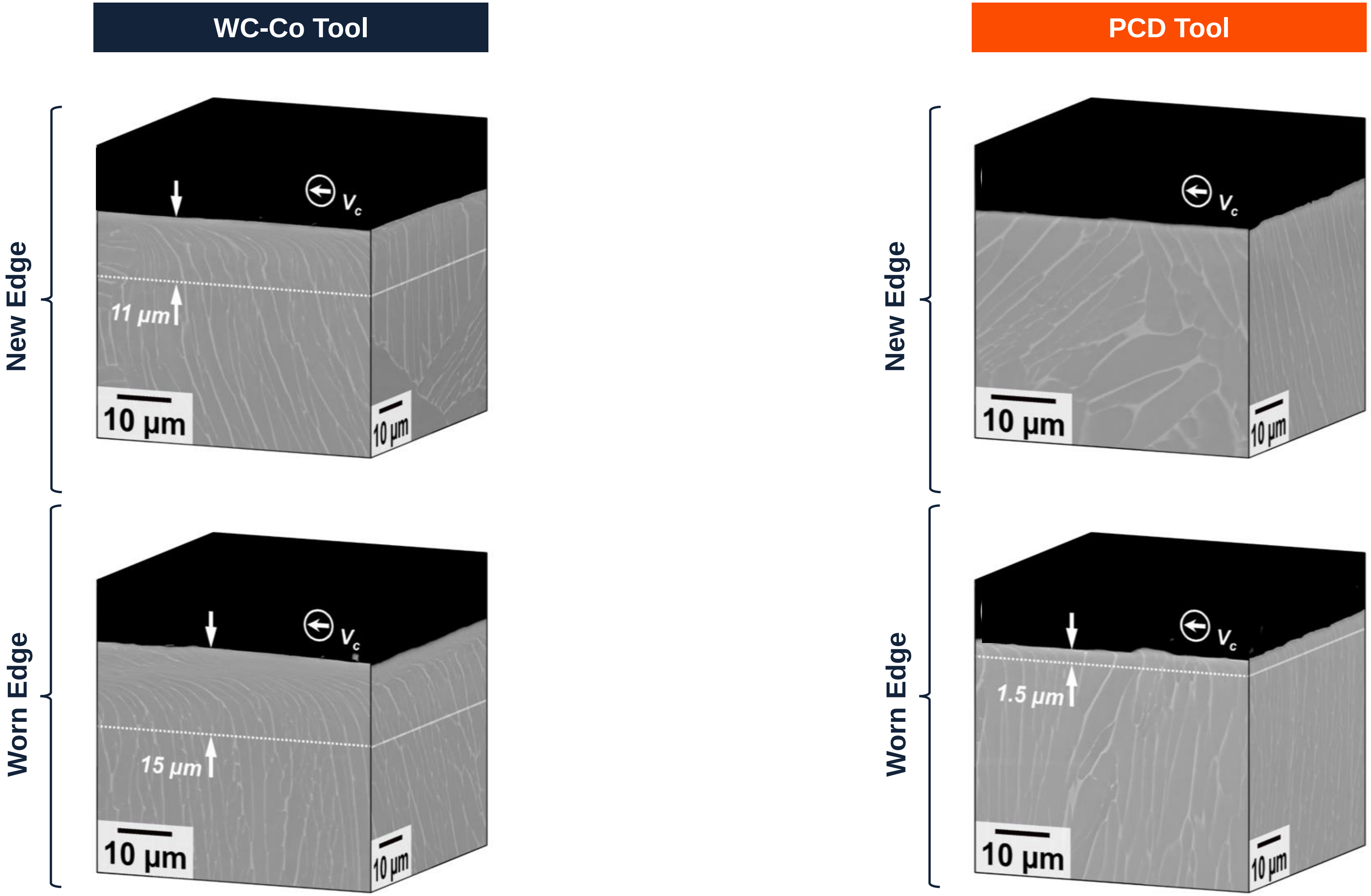
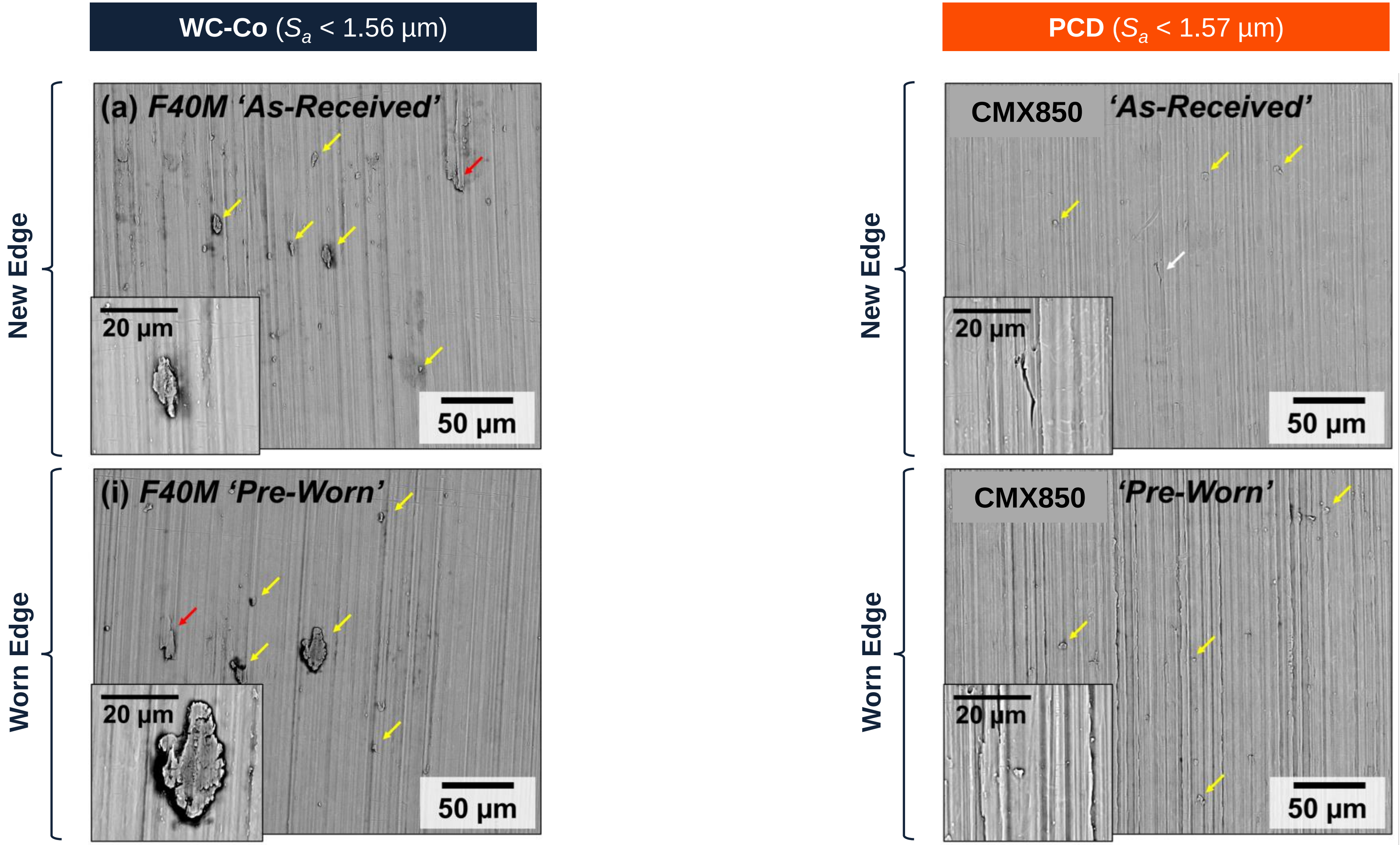


Results: Subsurface integrity



Results: Surface morphology



Results: Tool-workpiece interaction

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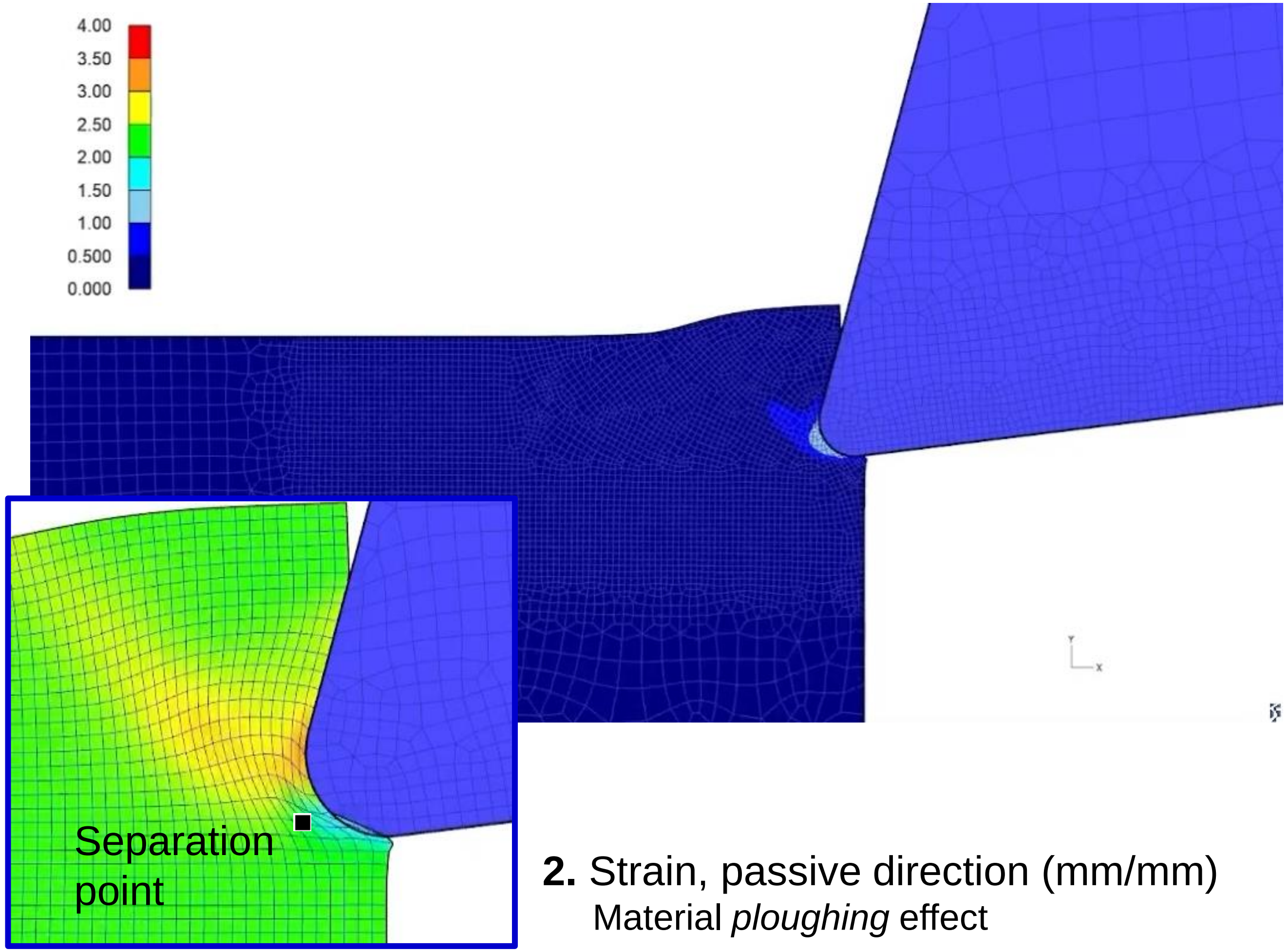
1. Effective strain (mm/mm)



2. Strain, passive direction (mm/mm)
Material *ploughing* effect

WC-Co tools:

- Larger cutting edge radii.
- Facilitate higher feed rates due to their toughness.

This promotes ploughing, leading to greater levels of damage and deformation.

PCD tools:

- Sharper cutting edge radii.
- Facilitate higher cutting speeds and lower feed rates due to high temperature hardness.

This reduces ploughing, leading to less mechanically imparted damage.

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Summary:

- Fine grain size and fracture resistance of Element Six CMX850 is critical to resist fracture during interrupted cutting of Ti-alloys
- Tool life optimised at the point where the tool degradation mechanism transitions from mechanical fracture → adhesive spalling
- Improved tool performance should focus on reducing mechanical impact through:
  - Material: Finer grain sizes with higher Co content
  - Geometry: Increasing rake angle aggressiveness
  - Strategy: Conventional milling ‘thin-to-thick’ chip generation
- PCD finishing has been shown to be capable of surface generation with low levels microstructural damage and surface defects

Thank you for listening

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