PVD Coatings, Cutting Tools and Workpiece Materials in Machining

- Coatings improve cutting tool performance
  - What does it mean to the customer
  - Machine shop economics
- Technical review of functional coatings
  - Understanding tool materials
  - Understanding workpiece metallurgy and machinability
  - Role of coatings in metal cutting
- New coatings introduced in the market
  - How do coatings fit the application
  - Coating applications guide

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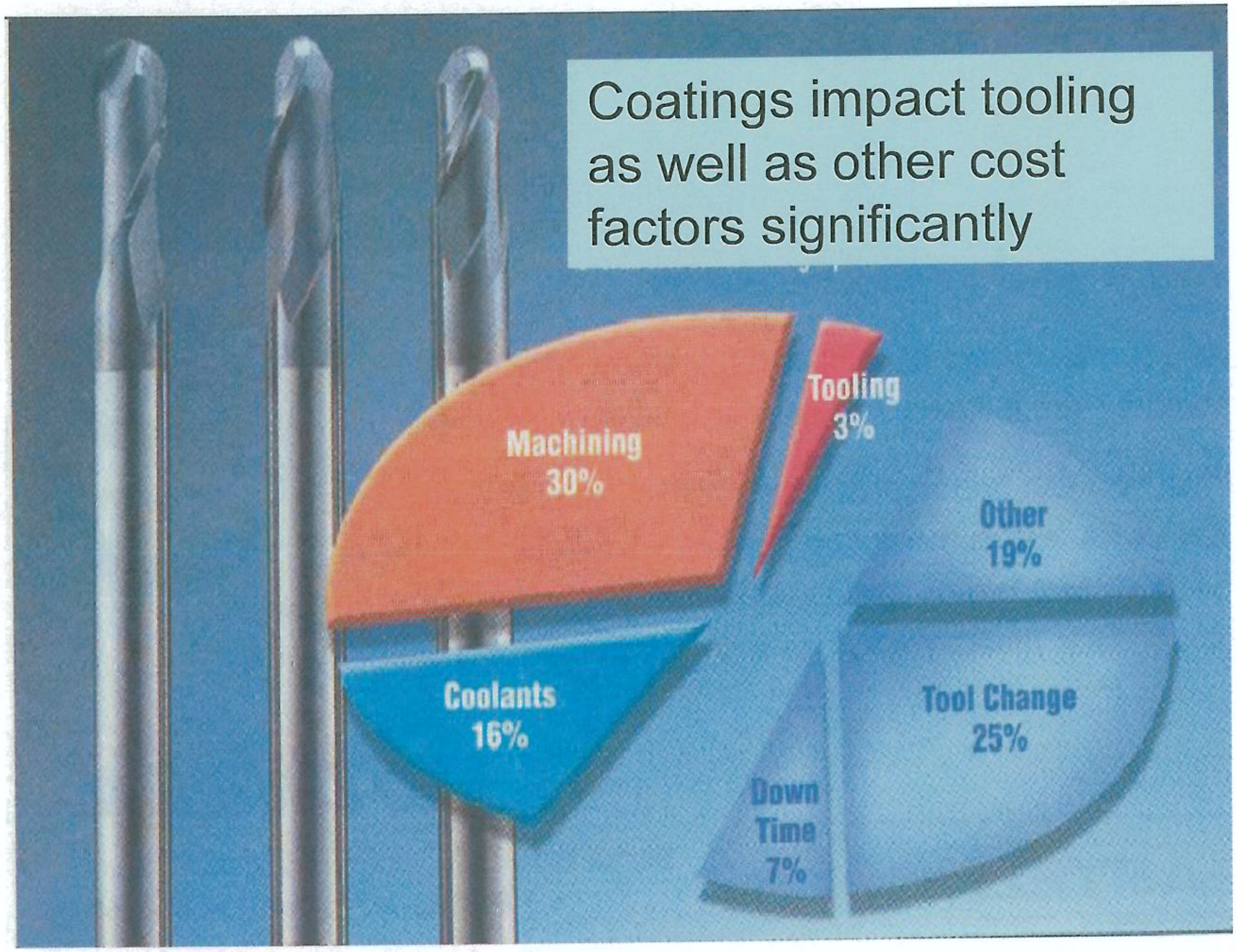
What does the coating do for the machine shop?

- Tool life increases, 30% to 200%, depending on application
  - save on tool costs
  - fewer tool changes and less downtime on machine
- Higher speeds (sometimes higher feed rates) are possible
- Dry (or near-dry) machining in certain operations
  - environmental impact
  - decrease coolant disposal costs

Increase productivity, decrease costs of machining.

Machine shop economics



Although coatings only show up as a percentage of tooling costs, the right coating can further reduce costs in machining, downtime, and coolants (and disposal) significantly.

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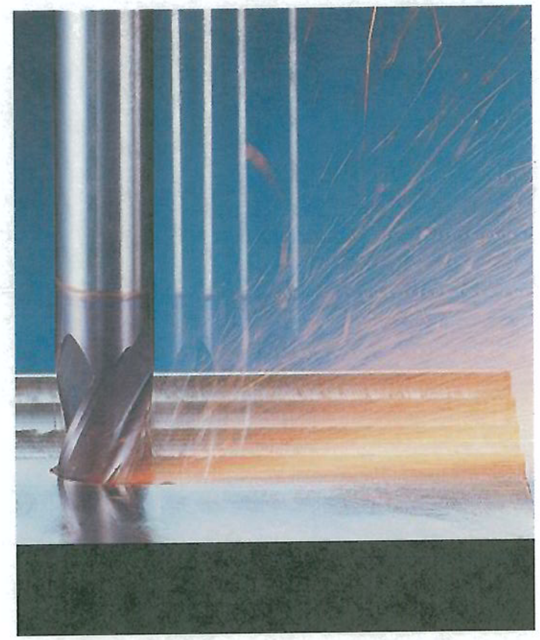
Technical review: materials science, tool coatings and machining processes

- Some basic considerations in metal cutting
- Workpiece mechanical properties and heat generation during machining
- Tool failure mechanisms
- Coatings enlarge the tool safe zone in operation
- Coating properties and control by PVD process
- Matching the coating to the application



Coating properties greatly determine the tool response to the wear environment.

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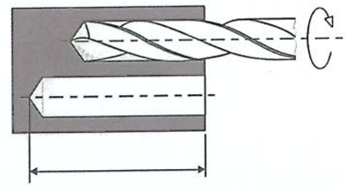
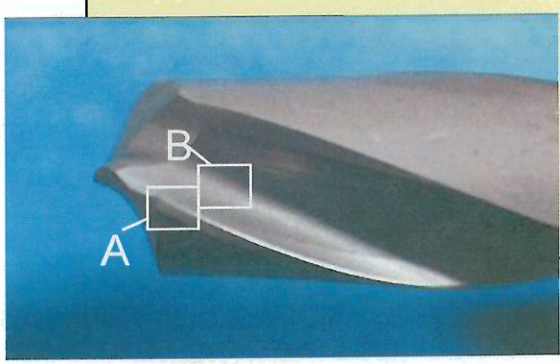
The metalcutting puzzle



tool performance factors	machining operations	workpiece materials
tool material coating edge geometry (with edge prep.)	turning, profiling grooving, threading drilling, tapping reaming, broaching milling, hobbing - speeds, feeds, doc - continuous to interrupted cuts	carbon, alloy steels cast irons stainless, superalloys aluminum alloys titanium alloys - surface finish - chip control



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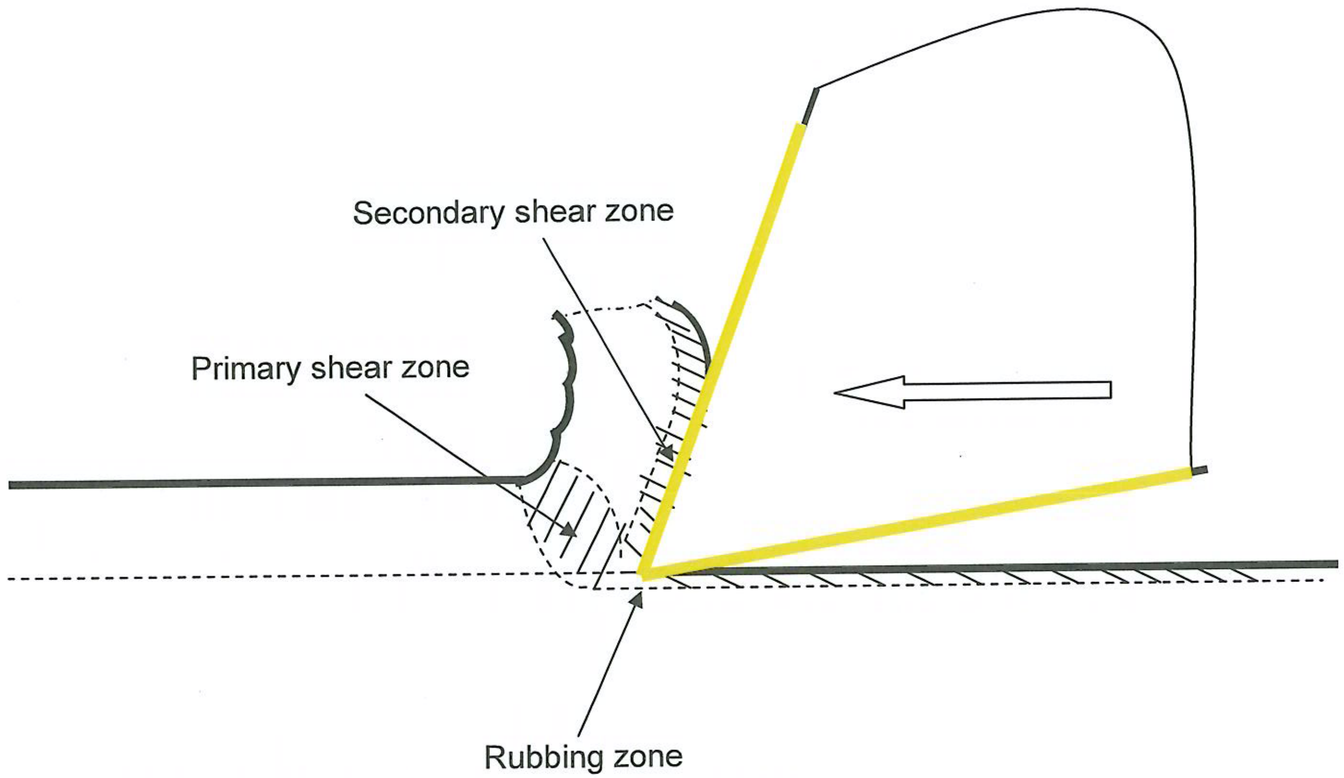
Workpiece – tool surface interactions: affected by the coating at the cutting edge



Heat originates from plastic deformation energy
a) of the workpiece at the primary shear zone

and at chip/tool contact areas governed by tribology/friction (i.e. coating) at
b) chip secondary shear zone / tool rake face
c) machined surface tertiary shear zone / nose/flank face of the tool

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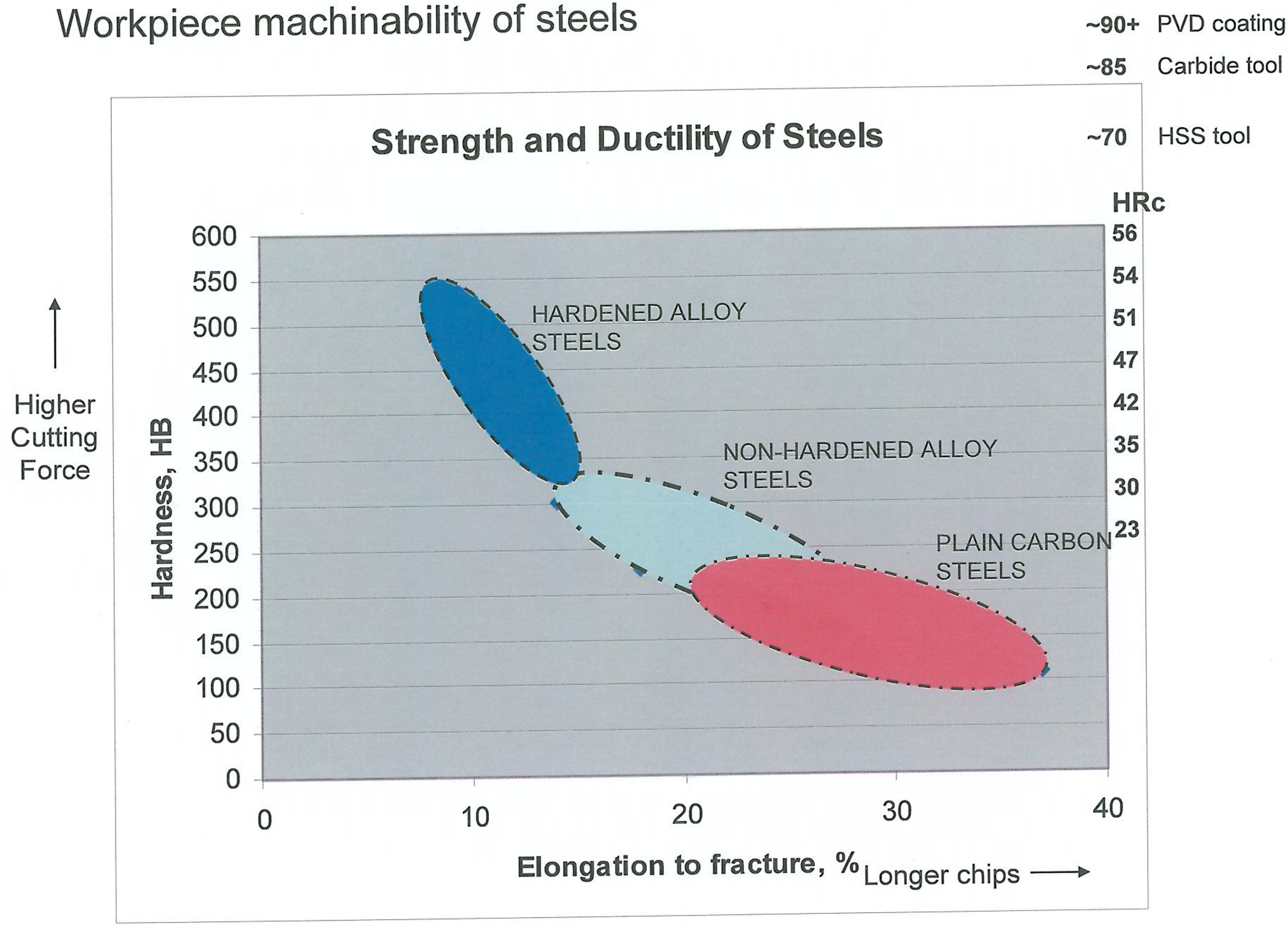
Workpiece machinability of steels



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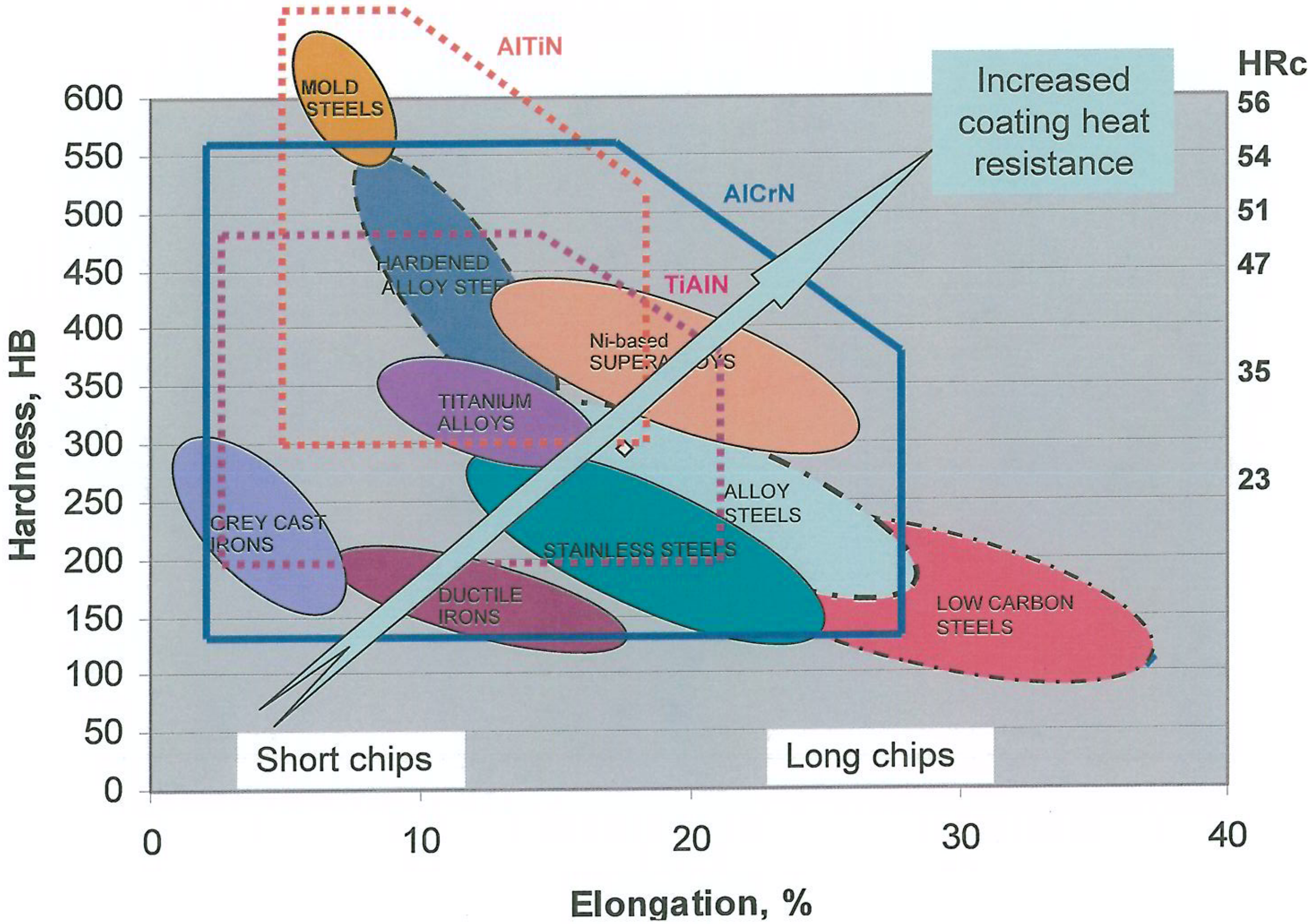
Relative machinability of materials



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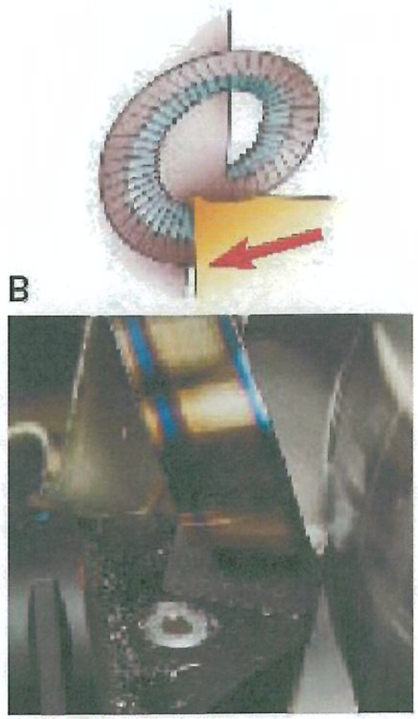
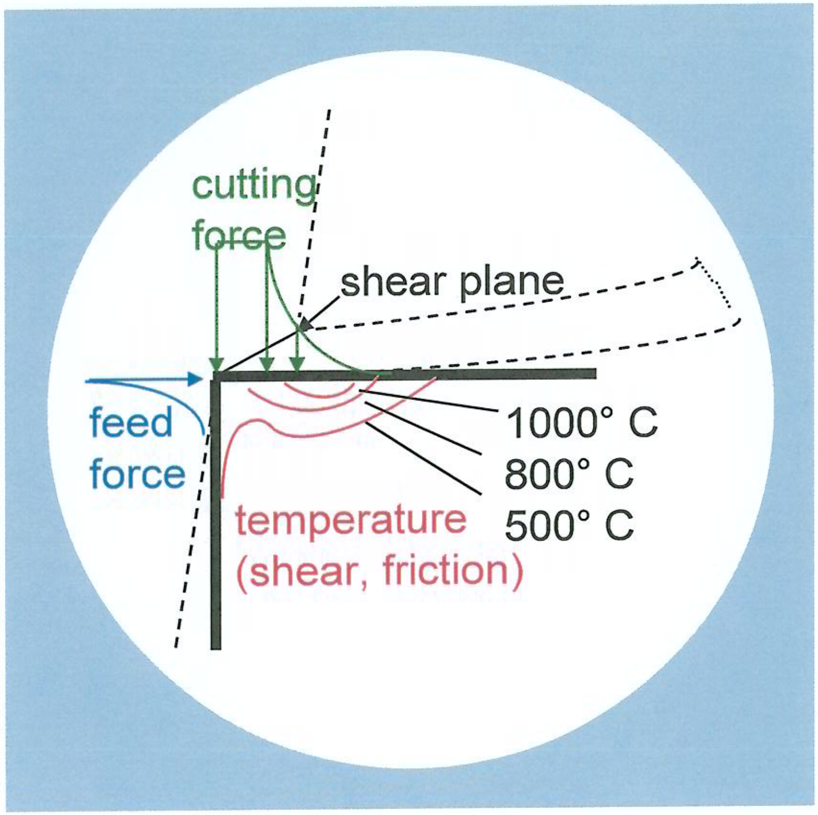
Long chip formation

- ductile metals - low carbon steel, aerospace aluminum, stainless
- continuous cutting (turning, threading, drilling,..)

- Long contact length and high temperature on rake face
- High surface shear forces
- Tendency for built-up edge



Require high chemical wear resistance, smoothness and best adhesion of coating.



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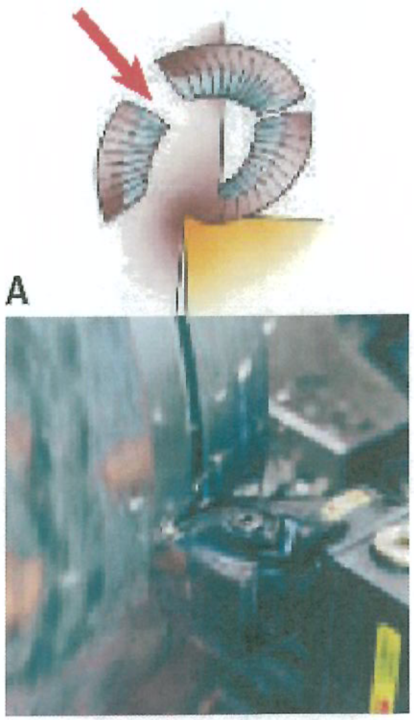
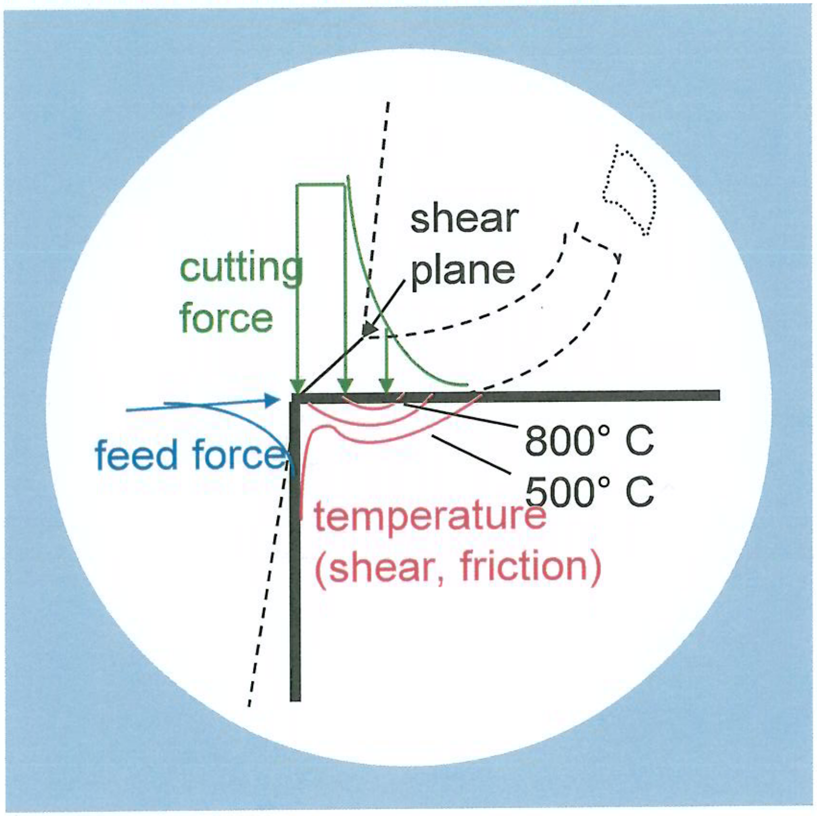
Short chip formation

- brittle metals: cast iron, automotive Al-Si, hardened steels
- interrupted cuts (milling, hobbing,…)

- Short chips, moderate temperature
- High normal cutting and feed forces

Require high abrasive wear resistance, compressive residual stress of coating.





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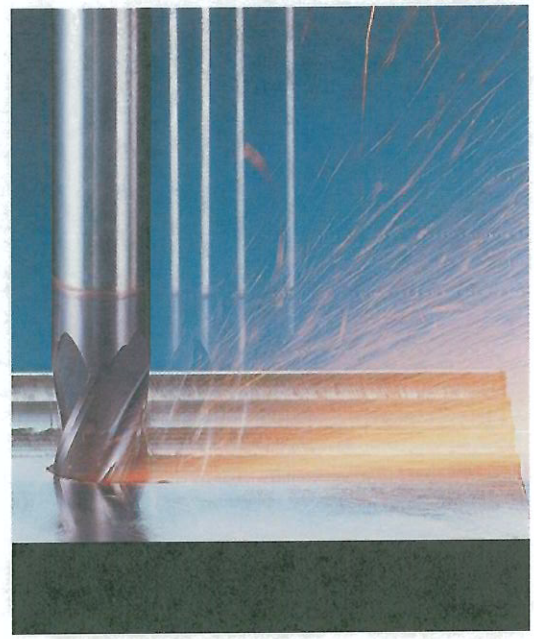
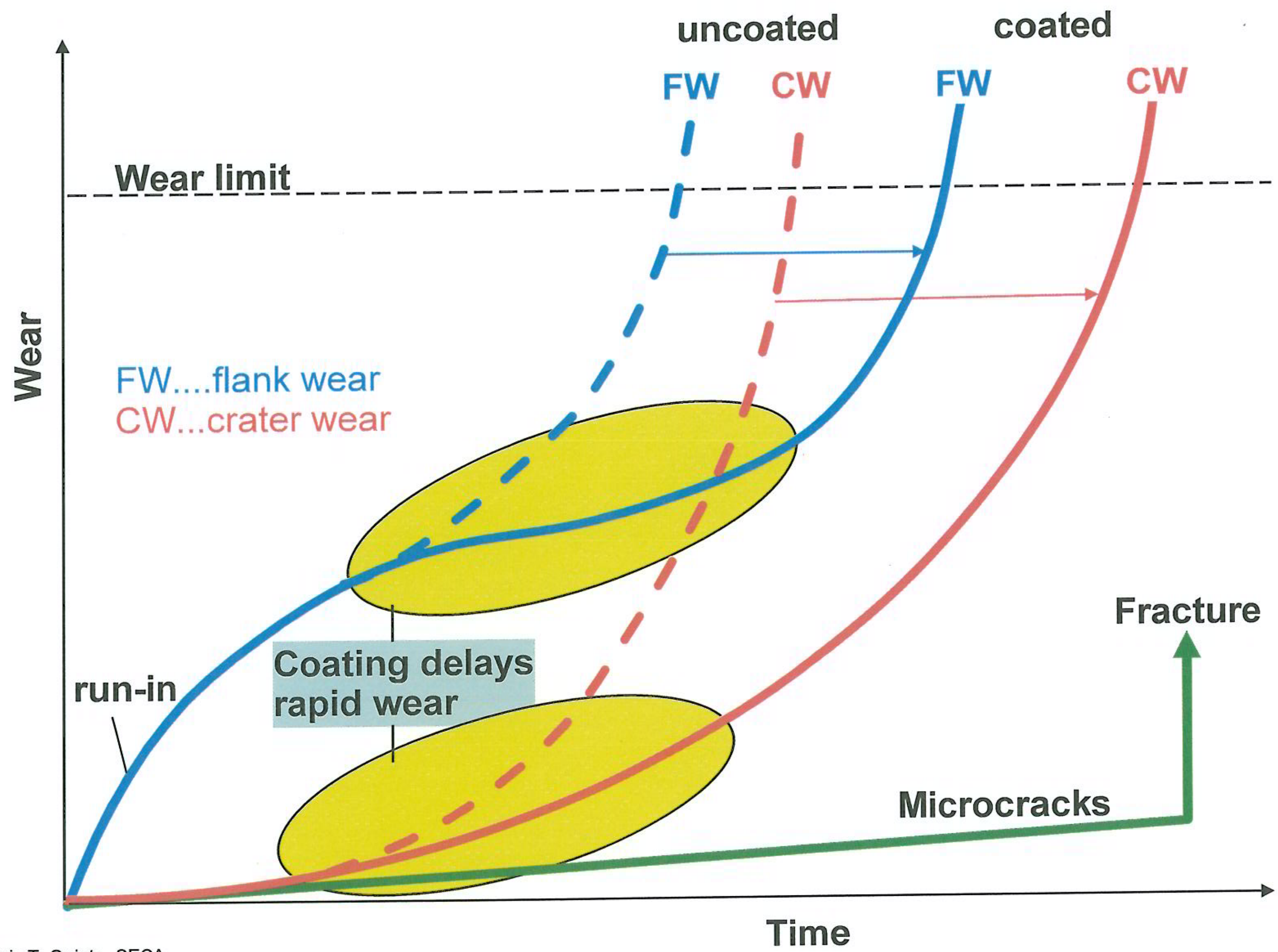


Coating properties greatly determine the tool response to the wear environment.

Schematic tool wear curves in metalcutting; the effect of protective hard coatings is to delay flank/crater wear and micro-cracking



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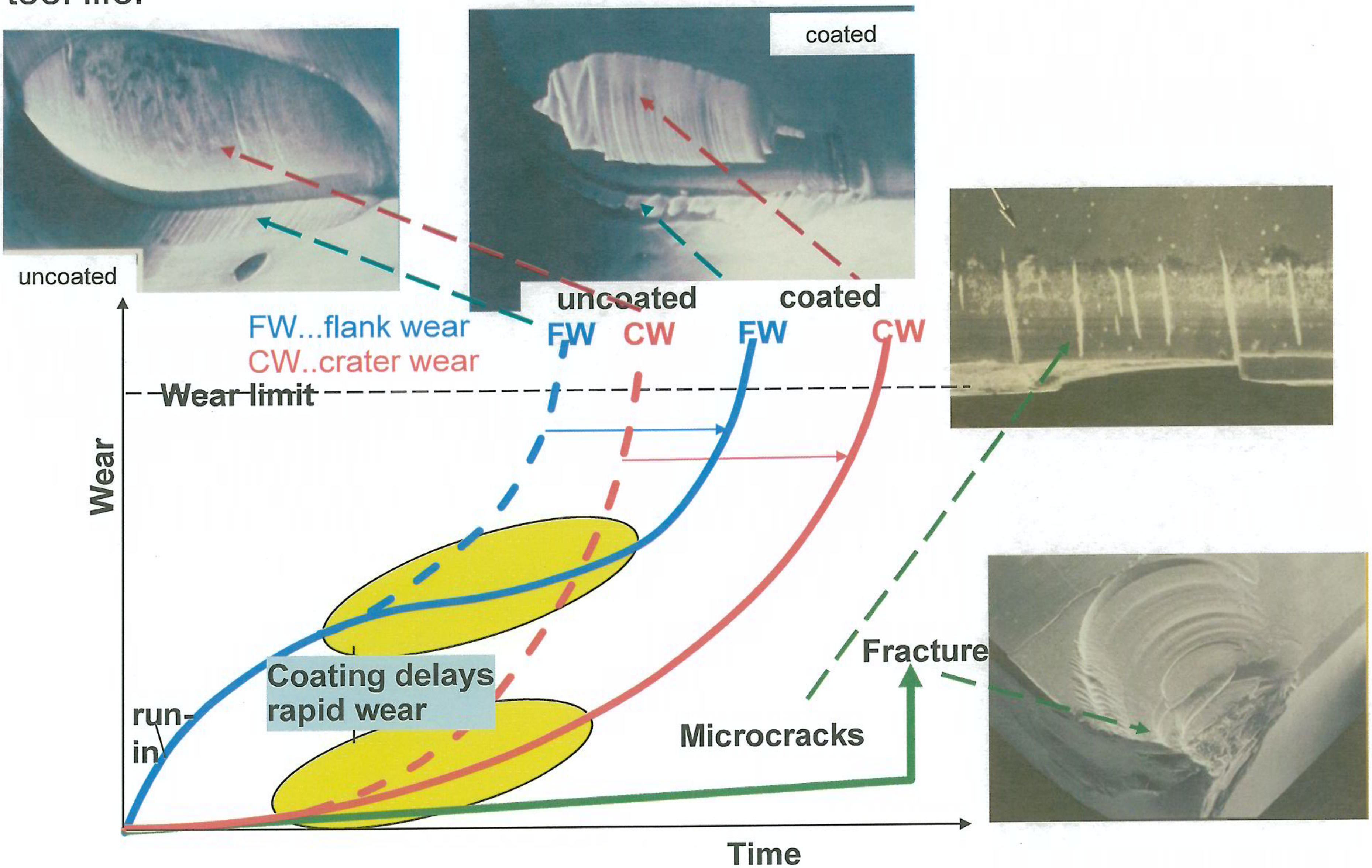
Whichever wear limit is reached first in a cutting operation determines the tool life.



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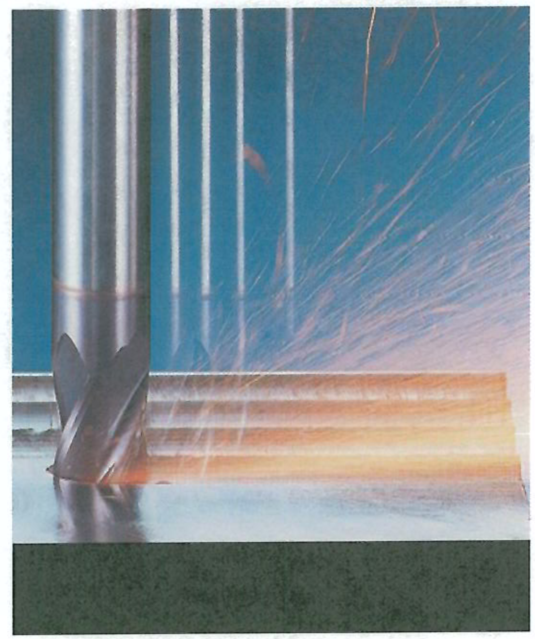

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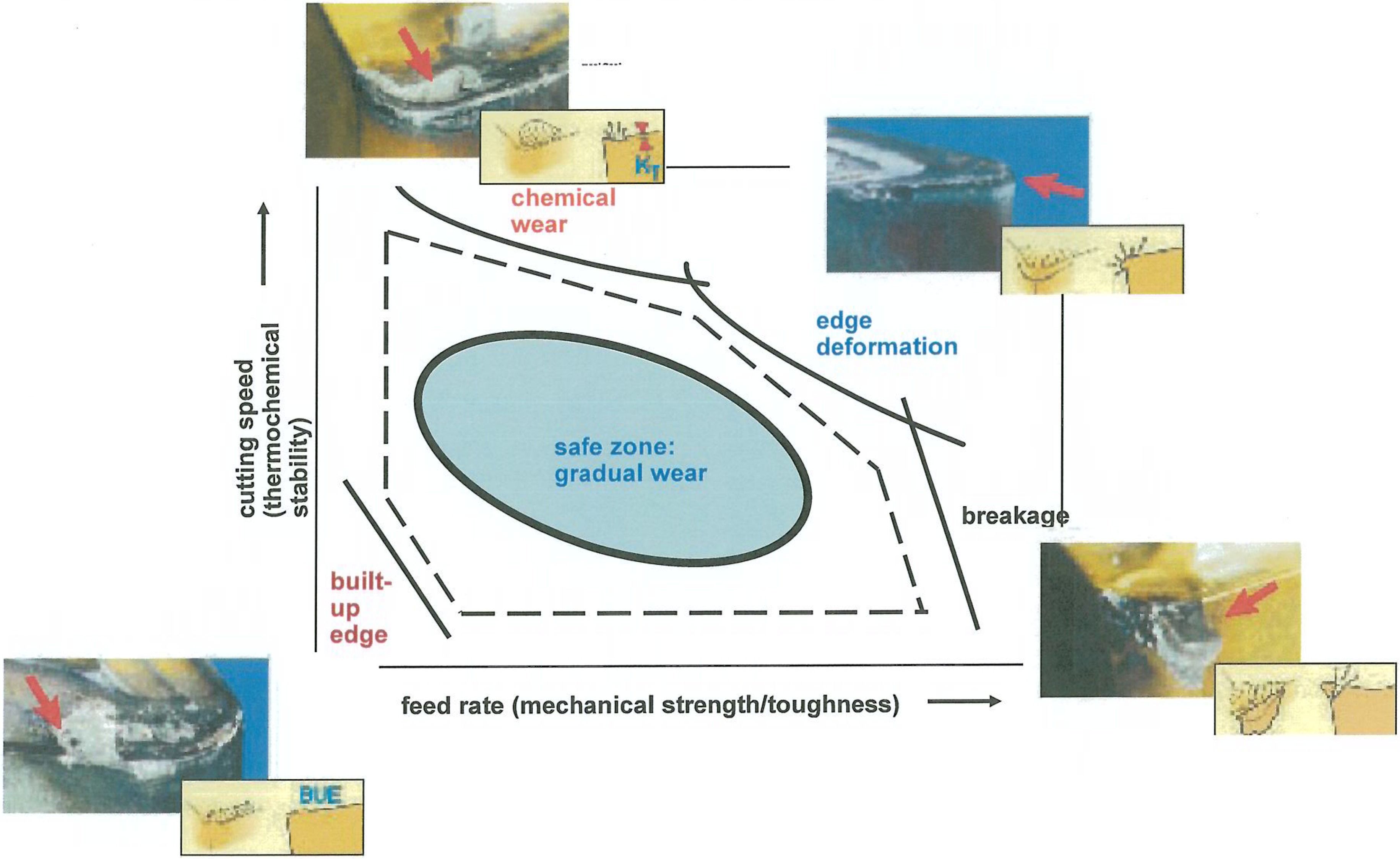
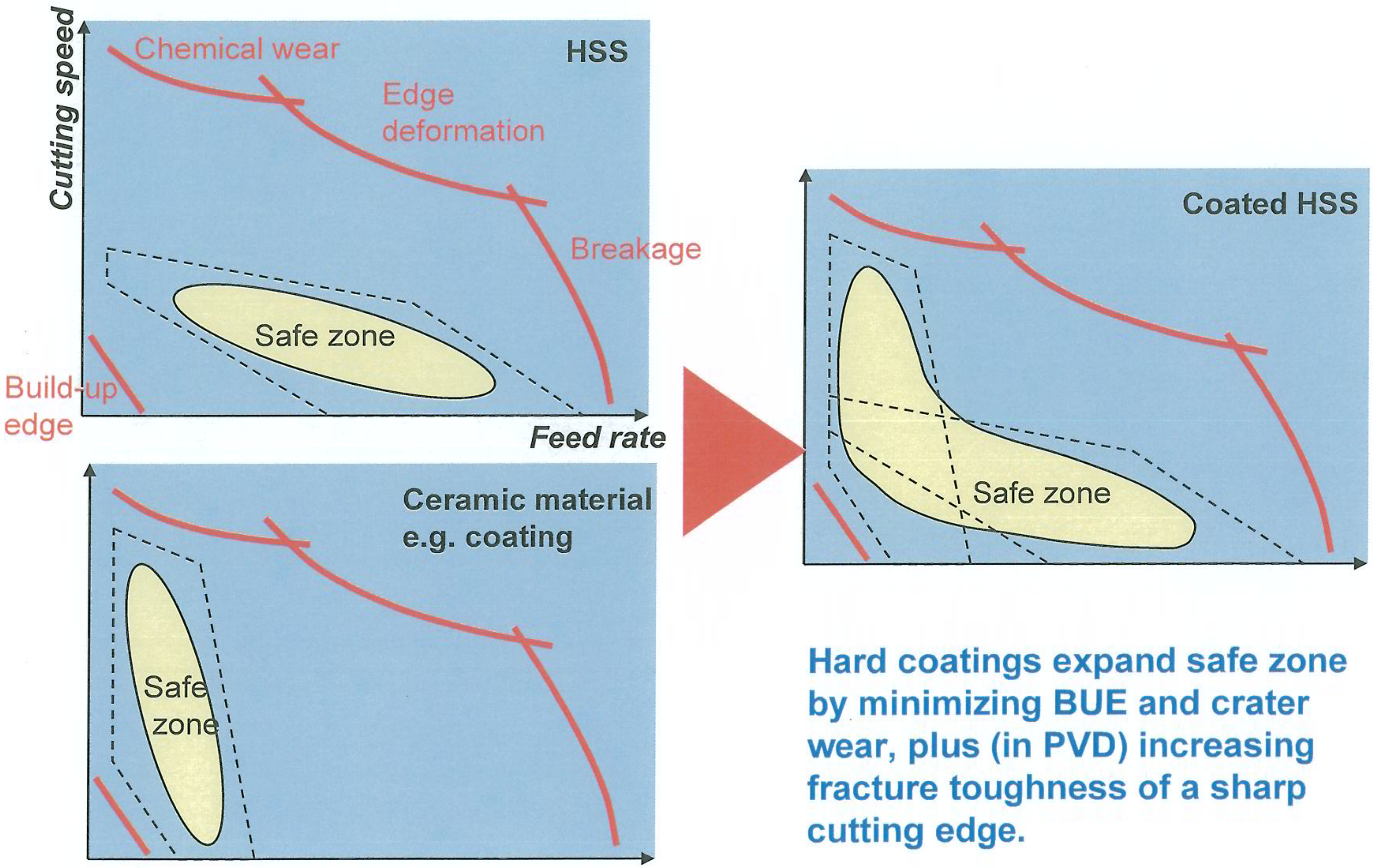
Tool wear modes are related to machining parameters (for a given cutting edge geometry).



Failure mode for different tool materials; synergy between tough subsrate and protective hard coating



Hard coatings expand safe zone by minimizing BUE and crater wear, plus (in PVD) increasing fracture toughness of a sharp cutting edge.

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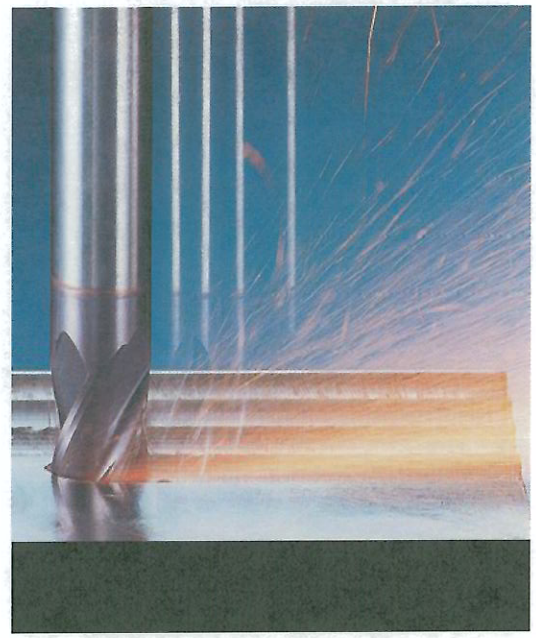

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Hard coatings at the cutting edge of carbide tools: PVD developments predominate the last decade

1970	CVD TiC
1975	CVD TiC / TiCN / TiN
	CVD TiC / Al_2O_3 / TiN
1980	CVD TiC / TiCN / Al_2O_3 / TiN...
	MTCVD TiCN
1985	PVD TiN
	PVD TiCN
1990	PVD TiAlN
	CVD Diamond
1995	PVD TiN / TiAlN / TiN / TiAlN...
	PVD TiB_2
	PVD TiN / TiCN /..MoS_2, TiAlN / WC-C
2000	PVD TiAlN multi-, nano-layers AlTiN
2005	PVD AlCrN, Al_2O_3

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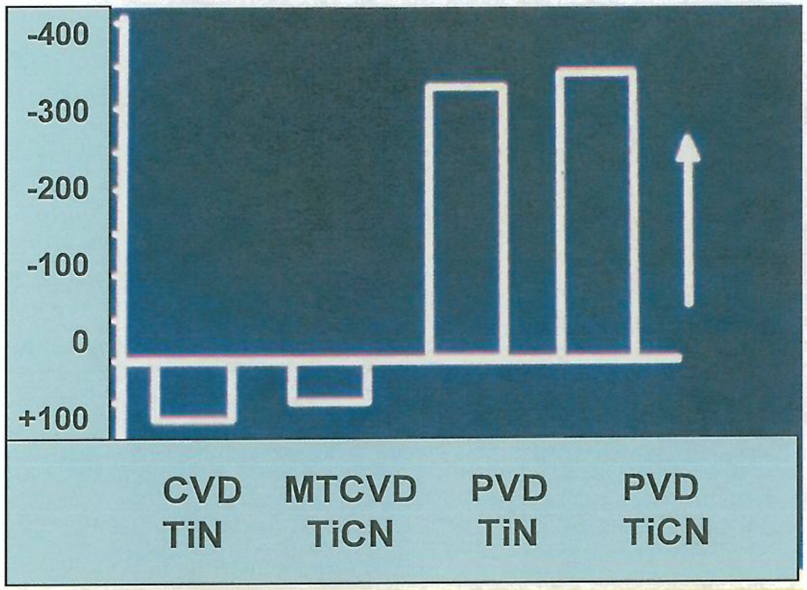
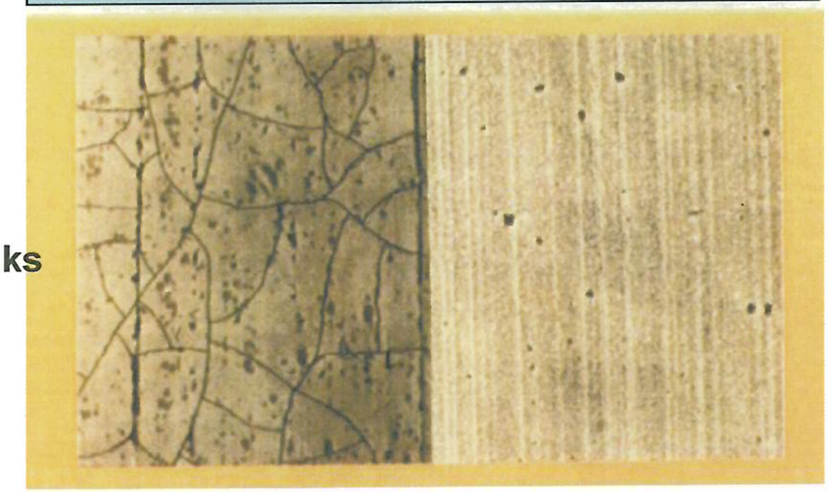
CVD vs. PVD coatings: different residual stress states, sharp edge capability are advantageous for PVD

Residual stress, kg/mm²



Resistance to mechanical fatigue stress

CVD thermal cracks



PVD crack-free

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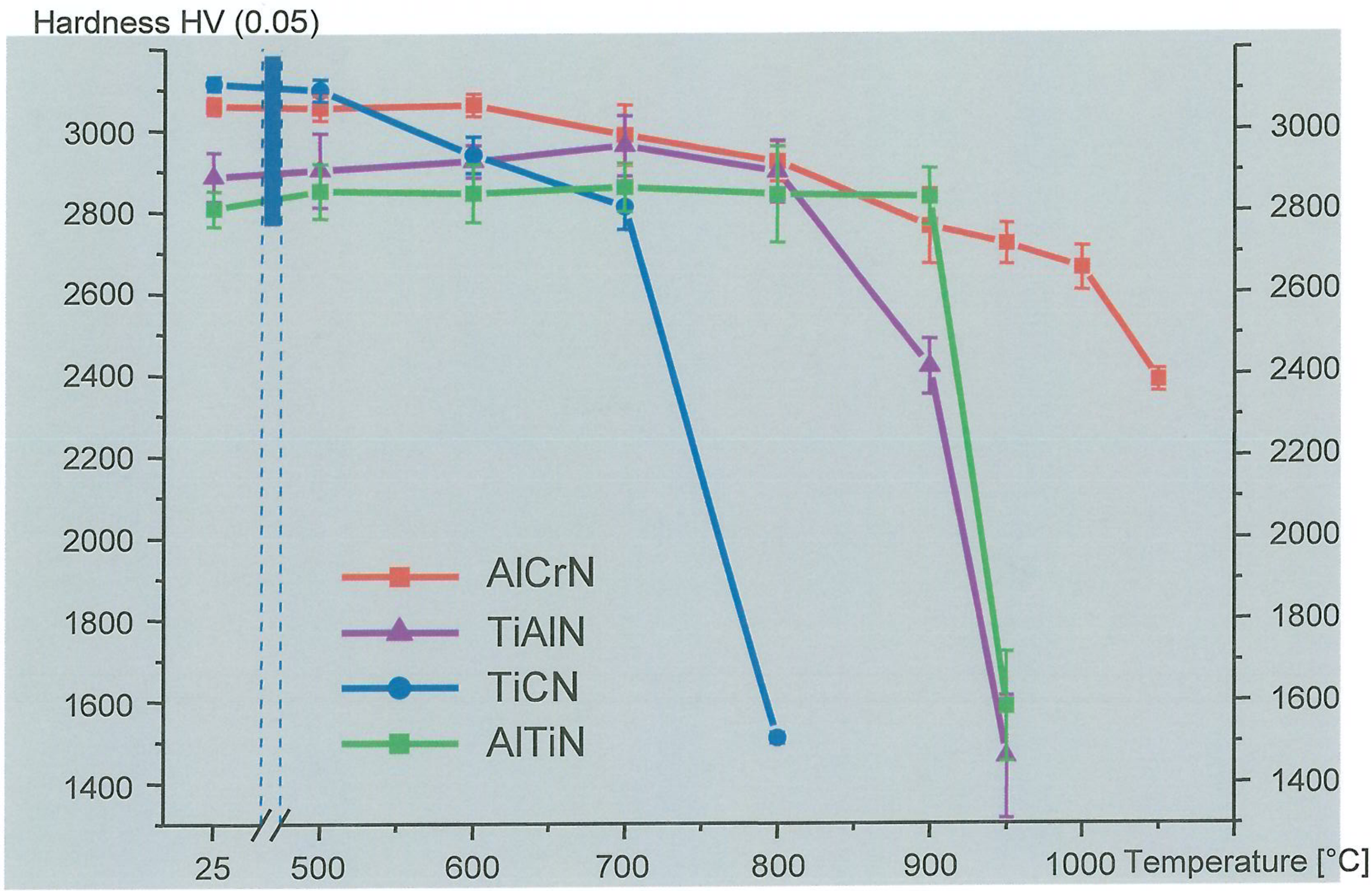
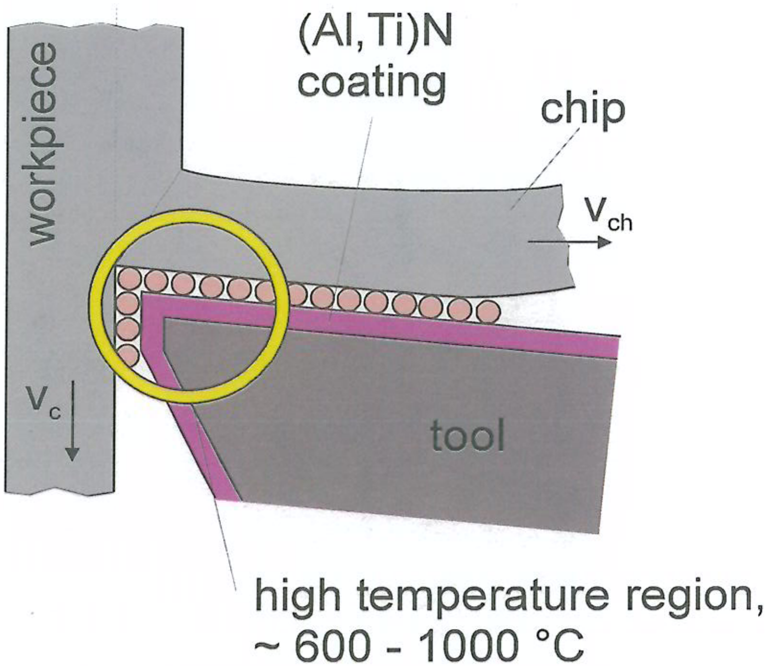
Continuous evolution of coating wear protective properties

Improved hot hardness

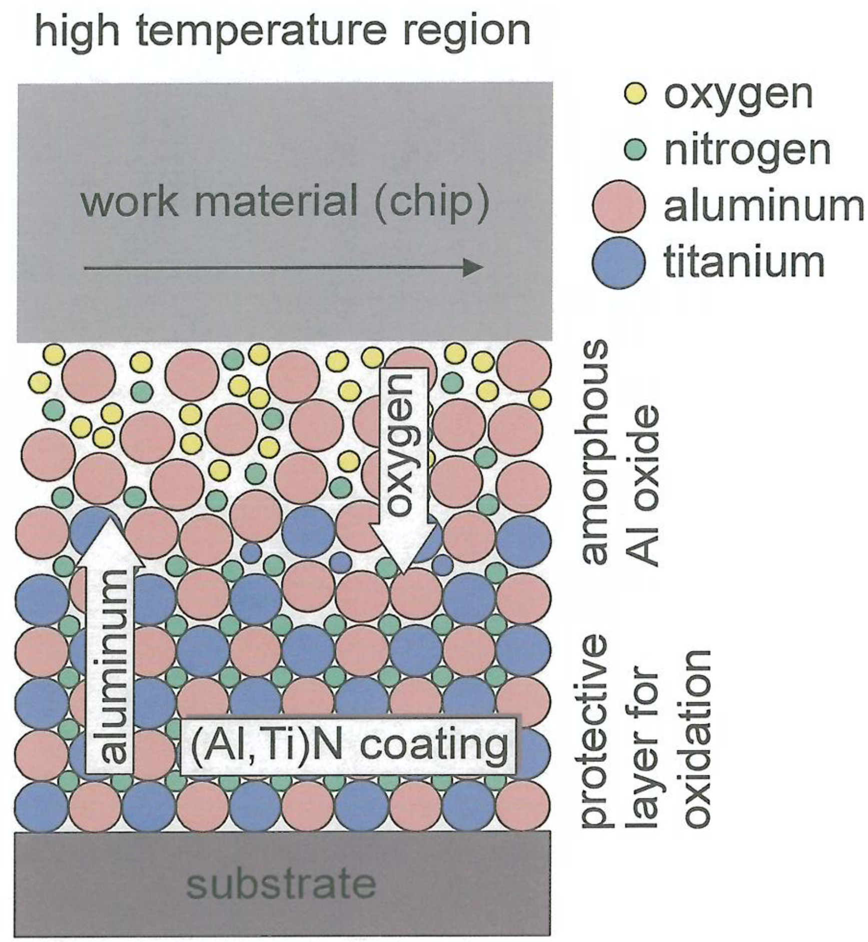


Oxidation model of (Al,Ti)N coating during metal cutting



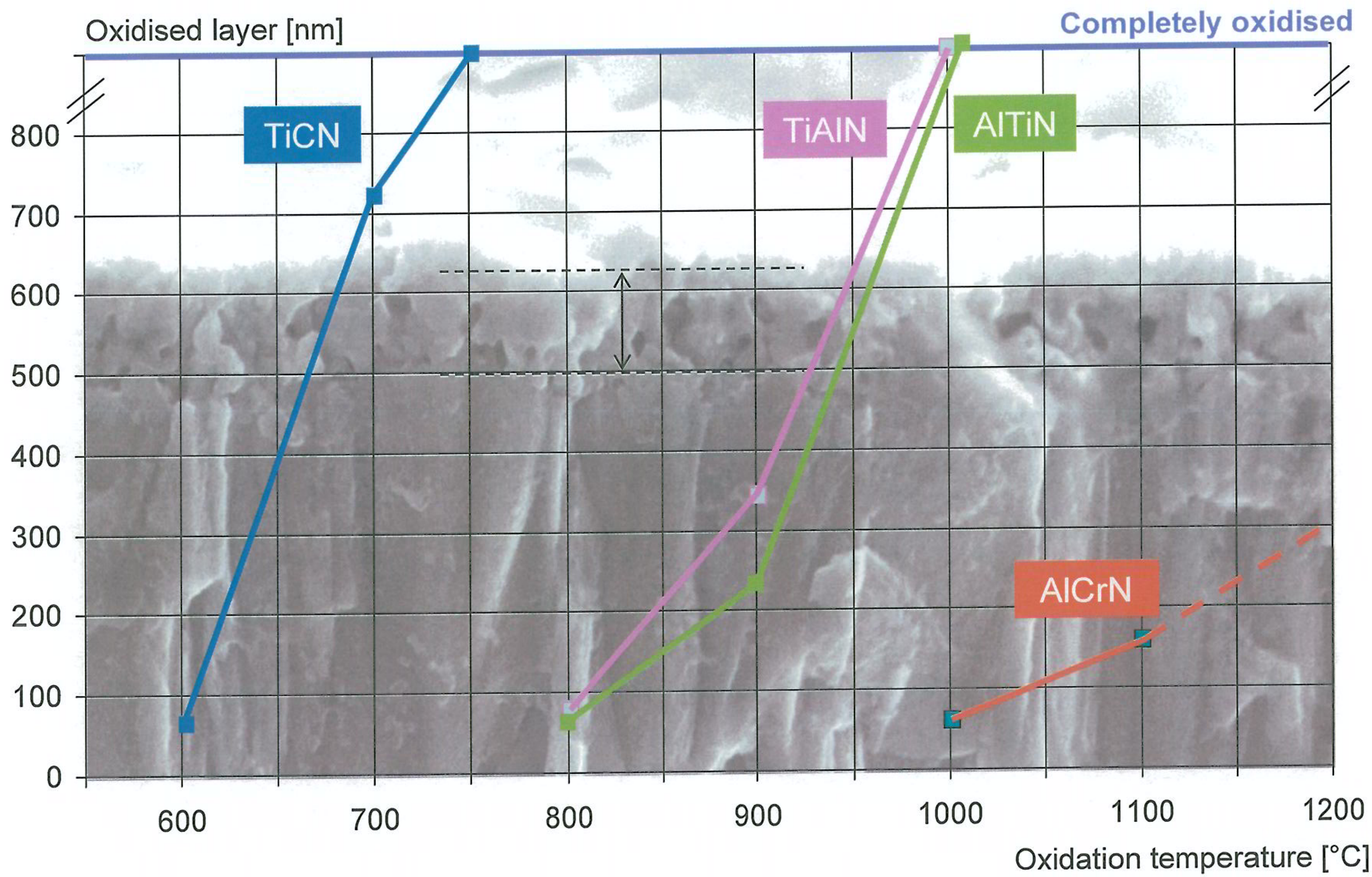
$TiN + O_2 \rightarrow TiO_x$

$(Al,Ti)N + O_2 \rightarrow AlO_x + TiO_x$



source: Kobelco, Japan

Improved oxidation behavior



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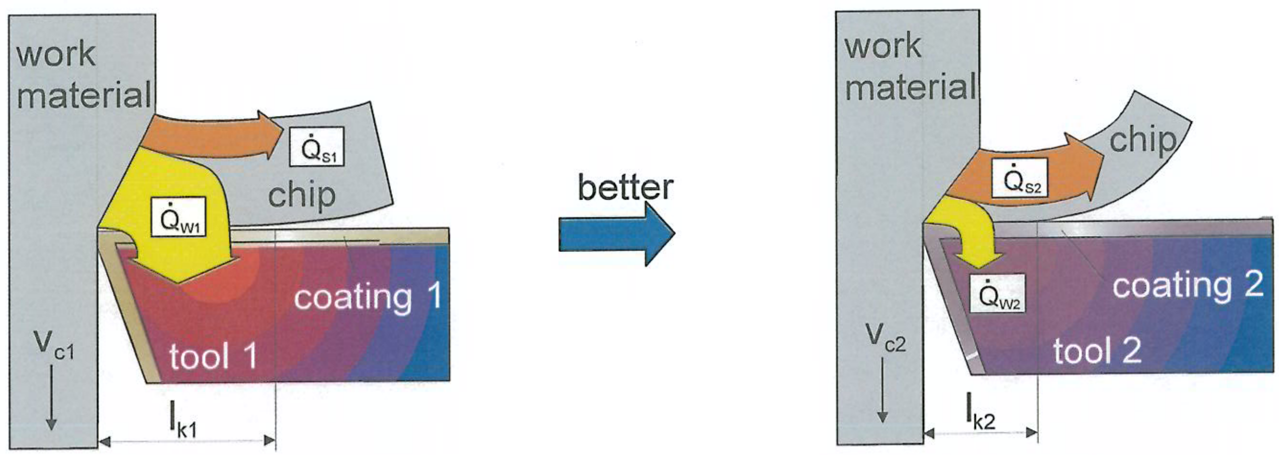
Effect of higher temperature stability and lower thermal conductivity of the coating: heat generation and heat transfer to tool substrate is decreased e.g., TiN => TiAlN



TiN-coated

TiAlN-coated

Variables affecting heat generation:

- Work material – fracture energy, strain-hardening coefficient, **thermal conductivity**
- **Friction coefficient at tool/chip contact surfaces**, contact length dictated by cutting edge geometry
- **Coating thermal conductivity**
- Metal cutting parameters (speed, feed, depth of cut)

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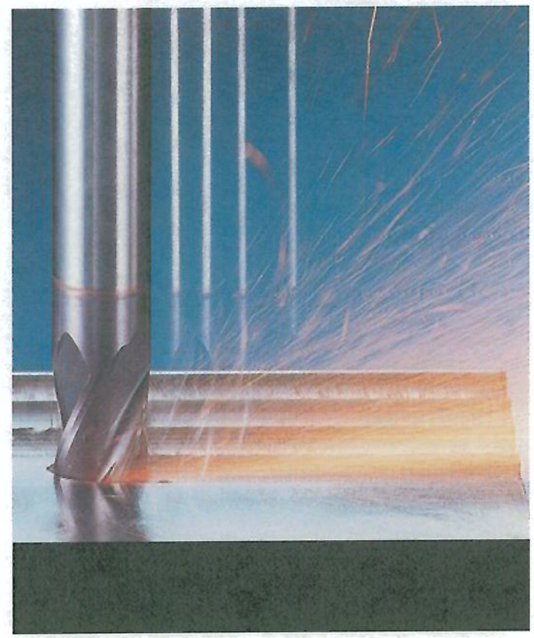

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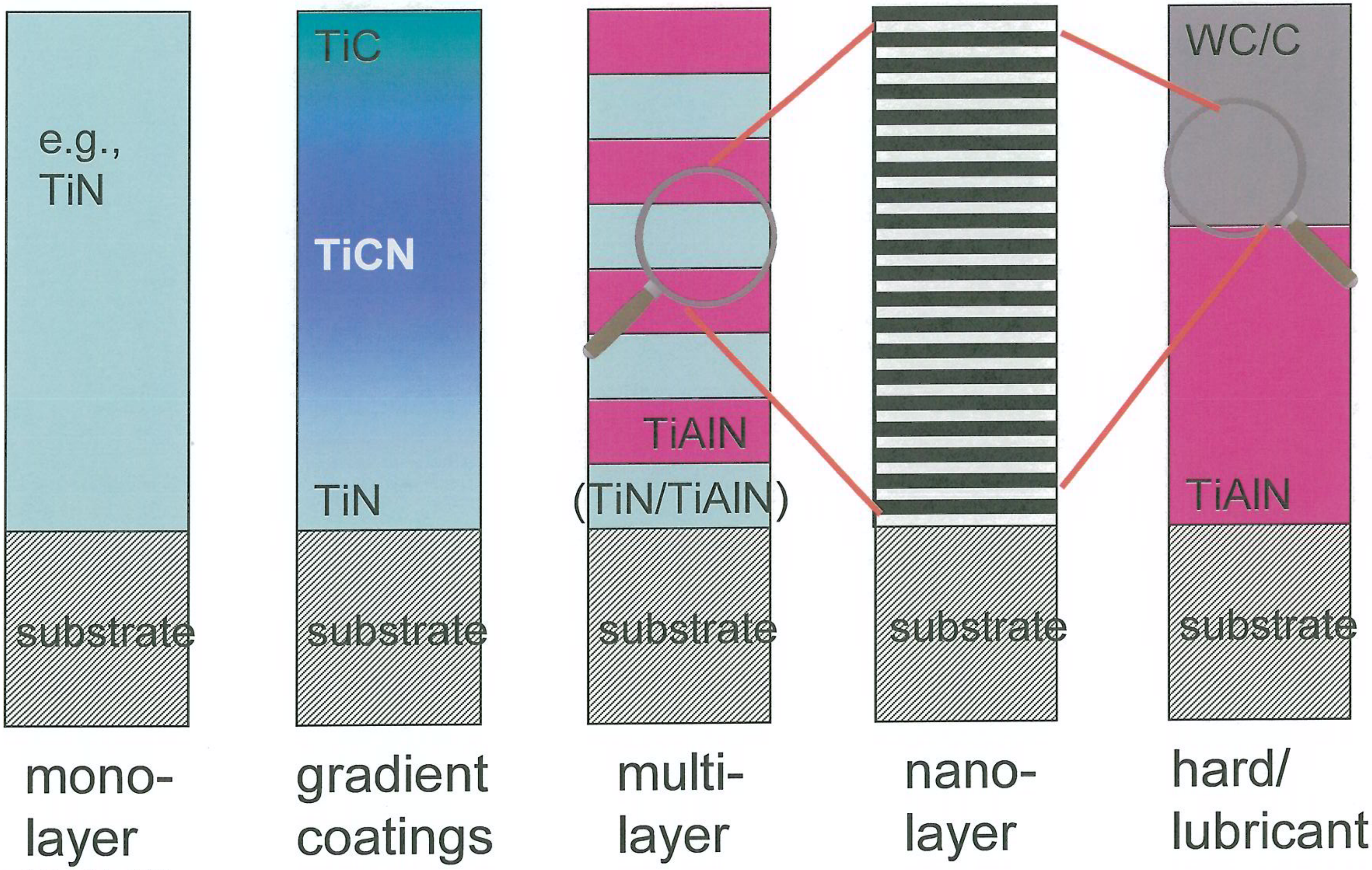
Microstructural designs of modern PVD coatings



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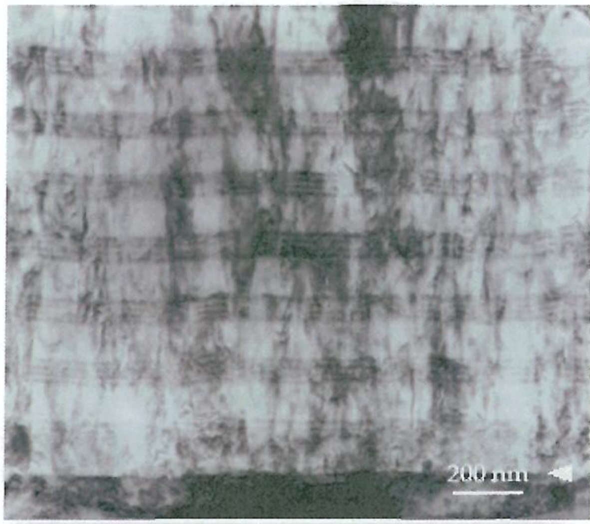
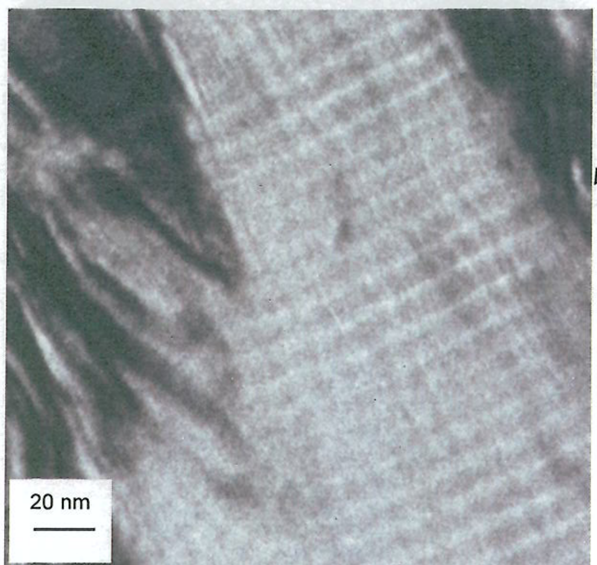
Microstructures of TiAlN PVD coating family





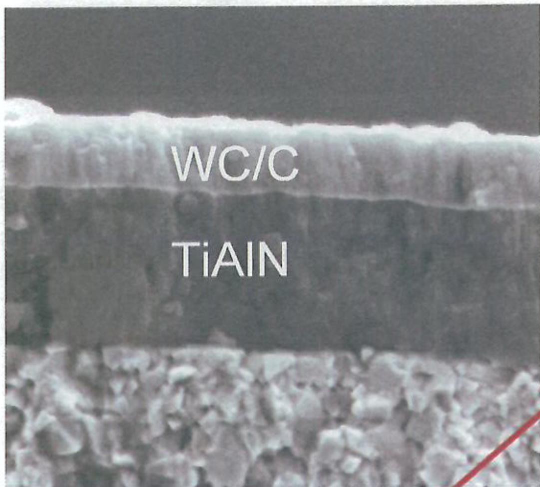
	Ti/Al ratio
Multilayer TiAlN/TiN	70/30
Nanolayer TiAlN/TiN	60/40
Nanolayer AlTiN.TiN	40/60

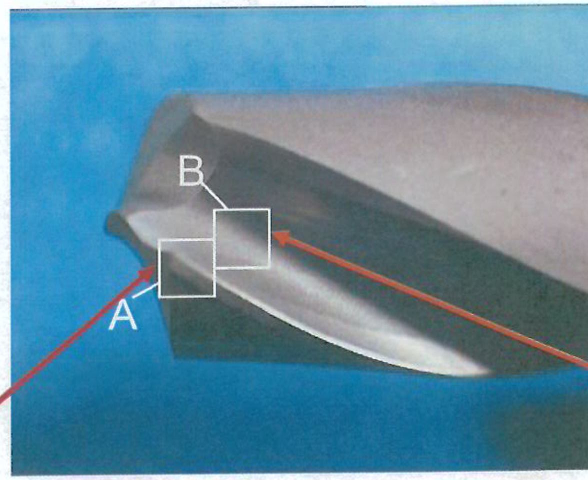
Controlled-stress coatings

Multilayered, nano-structured

TEM micrographs

Innovation: hard lubricant coating designed for dry drilling





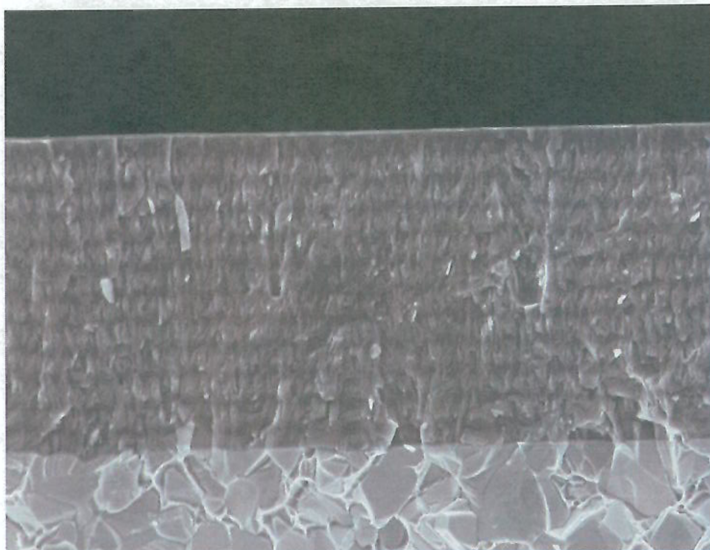
Lubricant layer (WC/C) in the flute

Hard layer (TiAlN) at the cutting edge

- High hardness (2600 HV 0.05)
- High temperature resistance (oxidation onset 800°C)
- Thermal barrier
- High chemical stability

- Amorphous carbon layer
- Hard & auto-lubricant layer
  -- 1000 HV 0.05
- Lamellar structure (WC/C)
  - Low friction coefficient
  - Prevents seizure
- Easy chip evacuation
  - Torque & cutting force reduction
- Efficient with or without lubricant

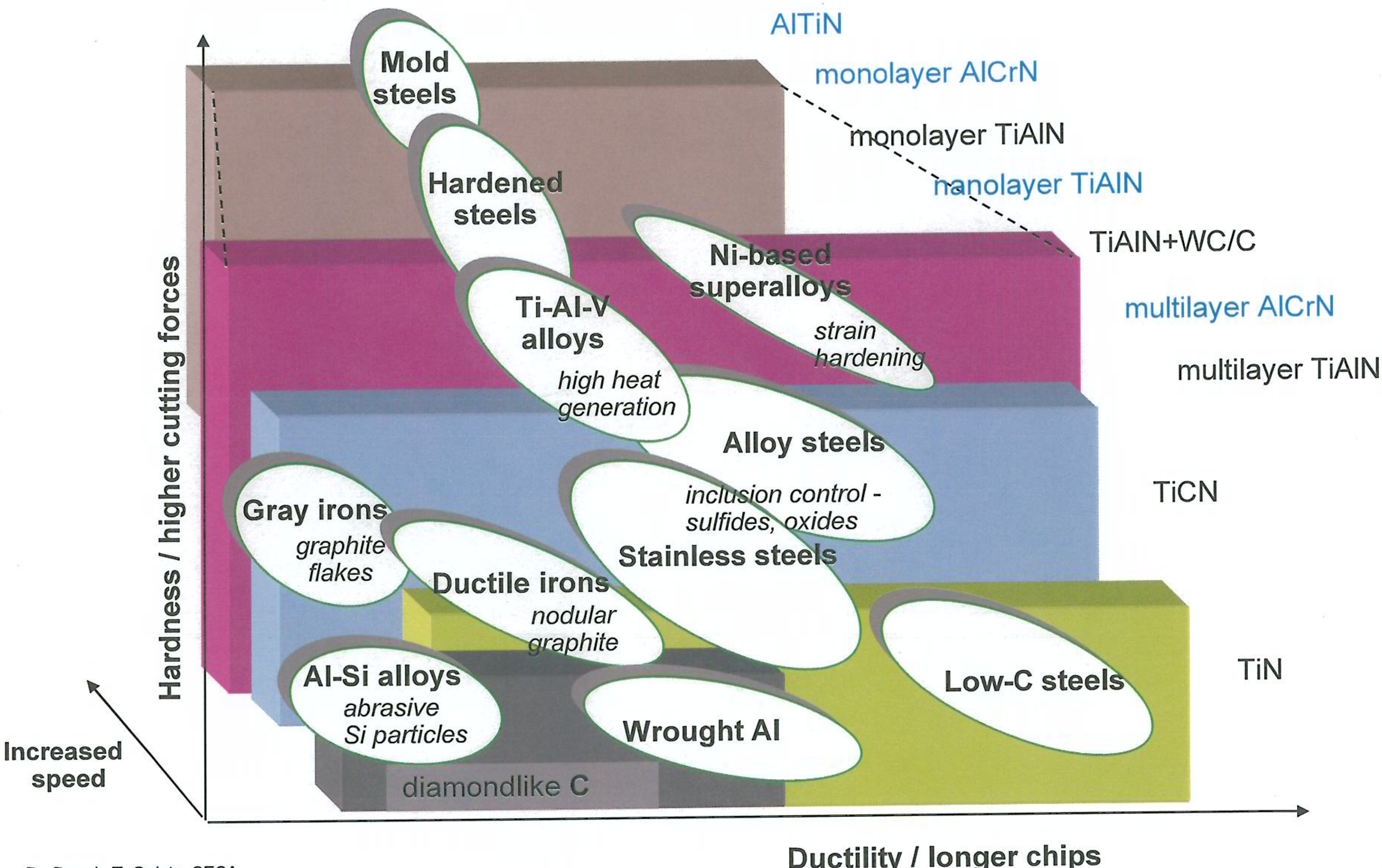
Multilayered AlCrN-base coating designed for drilling



Structure	AlCr-based multilayer
Hardness HV 0.05	3,000
Residual stress [GPa]	- 3.0
Max. service temperature [°F/°C]	**2000/1,100**
Coefficient of friction	0.25

- Very low wear due to high abrasion resistance
- Very low workpiece adhesion due to AlCr-base
- Excellent chip removal due to very smooth surface
- Highly homogeneous wear due to high shear strength of multilayer structure
- Less tendency towards cracking and improved toughness due to multilayer structure

Coating selection guide



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First generation coatings, applications

Coating Material	Titanium Nitride (TiN)	Titanium Carbonitride (TiCN)	Chromium Nitride (CrN)
Microhardness (HV 0.05)	2300	3000	1750
Coefficient of Friction against Steel (Dry)	0.4	0.4	0.5
Coating Thickness (μm)	1 - 4	1 - 4	1 - 6/10
Oxidation Onset Temperature	600 ˚C 1100 ˚F	400 ˚C 750 ˚F	700 ˚C 1300 ˚F
Coating Color	Gold	Blue - Gray	Silver - Gray
Key Characteristics	Basic TiN hard coating	Enhanced hardness and wear resistance over TiN	Excellent adhesion, high toughness, good corrosion resistance
Primary Applications	General purpose coating for cutting, forming, plastic molding	Cutting carbon steel, alloy steel and cast iron	Machining copper; metal forming; plastic molding

Later generation coatings, properties, applications

Coating Material	Titanium Aluminum Nitride (TiAlN)	Titanium Aluminum Nitride (AlTiN)	Titanium Aluminum Nitride/ Tungsten Carbide/ Carbon (TiAlN/ WC/C)	Aluminum Chromium Nitride (AlCrN)	Aluminum Chromium Nitride (AlCrN)-based
Microhardness (HV 0.05)	3300	3300	3000	3200	3000
Coefficient of Friction against Steel (Dry)	0.35	0.4	0.2	0.35	0.25
Coating Thickness (micron)	1 - 5	1 - 4	2 - 6	2 – 5	2 - 4
Oxidation Onset Temperature	900 °C 1650 °F	900 °C 1650 °F	800 °C 1470 °F	1100 °C 2000 °F	1100 °C 2000 °F
Coating Color	Violet - Gray	Blue - Gray	Black - Gray	Blue - Gray	Copper
Key Characteristics	Nanolayered coating, high oxidation resistance	Smooth morphology, higher oxidation resistance ("AlTiN")	Combined hard and lubricant coating layers	Highest oxidation resistance and hot hardness for high temperature wear resistance	Multilayered, smoothened coating for balanced high temperature wear resistance and heat conductivity
Primary Applications	Broad-based coating for cutting all steels, cast iron, stainless steel; dry machining possible; forming; die-casting	For carbide tool machining of hard mold steels (>50 HRc), aerospace titanium alloys, stainless steel, Inconel	For improved chip flow and possible dry machining e.g. in drilling, tapping; avoids buildup edge	For general wet/dry hobbing, milling of steels (<54 HRc), cast iron, aerospace Inconel; titanium alloys; for CBN inserts; punching, hot forming tools	Specialized for drills; proven on carbon steels, cast iron, stainless steels; including deep hole application

Carbon-based coatings, properties, applications

Coating Material	Tungsten Carbide/ Carbon (WC/C)	Diamondlike Carbon	Crystalline Diamond
Microhardness (HV 0.05)	>1000	>2000	>8000
Coefficient of Friction against Steel (Dry)	0.1 - 0.2	0.1 - 0.2	0.15 - 0.2
Coating Thickness (μm)	1 - 4	1 - 3	6 - 20
Oxidation Onset Temperature	300 ˚C 570 ˚F	300 ˚C 570 ˚F	800 ˚C 1470 ˚F
Coating Color	Black - Gray	Black - Gray	Silver - Gray
Key Characteristics	High lubricity and resistance to adhesive wear	Enhanced sliding wear capacity with high lubricity	Hardest coating, best abrasive wear resistance
Primary Applications	Precision components; plastic molding	Precision components; forming, molding ; cutting aluminum alloys	Machining graphite, fiber-reinforced plastic, pre-sintered carbide, non-ferrous metals, wood; for carbide tools <6% Co, available from Euro Diamond Coating Center