

Solution Wear

- Carbide cutting tools (not HSS steel tools) in cutting ferrous alloys at high speeds

Mechanical Behavior Dominated Wear

- Friction and wear controlled by *mechanical* behavior of materials
 - Friction due to plowing and asperity deformation
 - Delamination wear
 - Abrasive wear (Even some cutting tools -- HSS, Alumina)
 - Erosive wear
 - Fretting wear
 - Wear by plowing of the surface by wear particles and asperities

Friction and wear controlled by *Chemical* behavior of materials

- Solution wear (e.g., carbide tools)
- Friction due to adhesion (at high sliding speeds and high loads)
- Adhesive wear (at high sliding speeds and high loads)
- Oxidative wear (rare)
- Wear due to melting of the sliding interface (mostly in polymers)

Consider the wear of a cutting tool

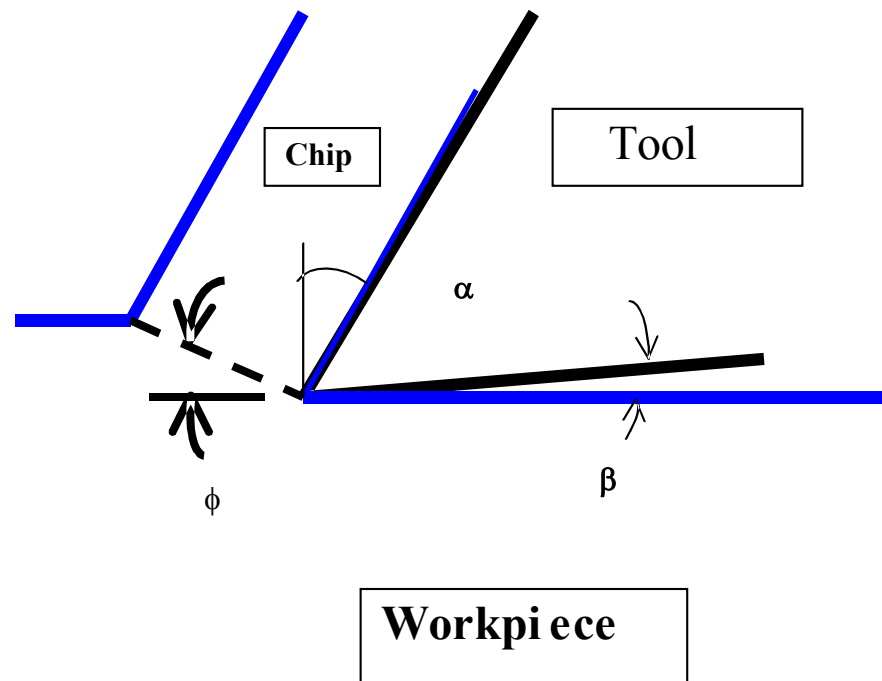
- When steel is cut at high speeds using a cutting tool, what is the wear mechanism?
- How can we make the tool last longer?
- How can we cut the workpiece at a higher speed?

The Causes of Solution Wear

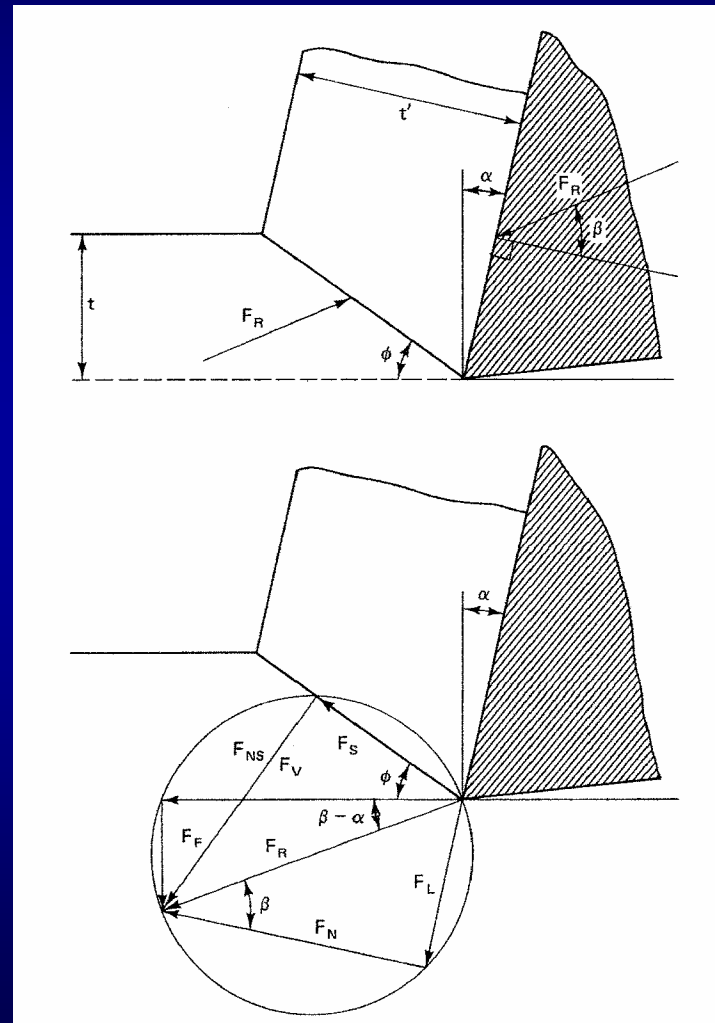
- Chemical reaction
- Formation of a solution between the materials in contact to decrease the free energy
 - Wear of tungsten carbide tools
 - Diamond in cutting ferrous metal

Introduction to Metal Cutting

Chip Formation



Cutting Forces & Chip Formation



Tool Wear

Diagram removed for copyright reasons.

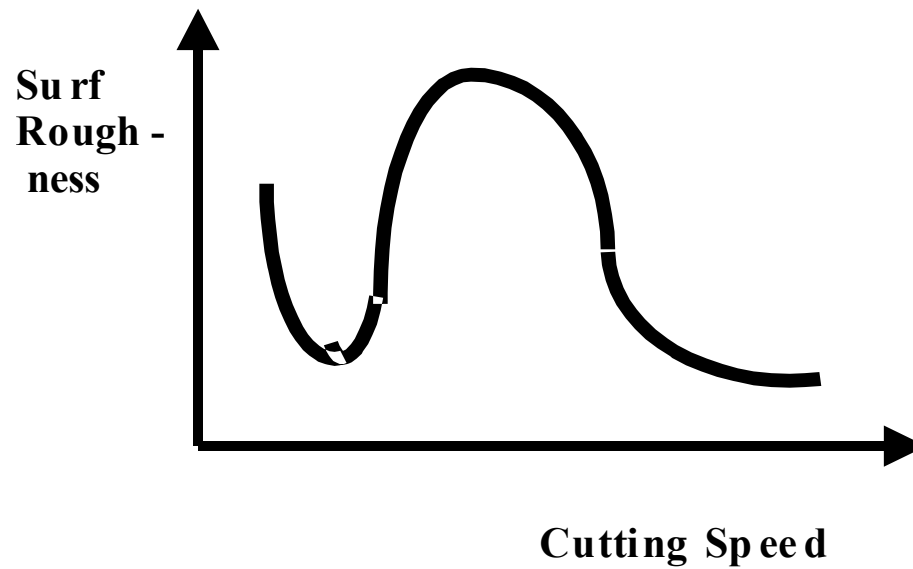
See Figure 8.8 in [Suh 1986]: Suh, N. P. *Tribophysics*. Englewood Cliffs NJ: Prentice-Hall, 1986. ISBN: 0139309837.

Chip Formation

Diagram removed for copyright reasons.
See Figure 8.2 in [Suh 1986].

Introduction to Metal Cutting

Surface Roughness vs Cutting Speed



Introduction to Metal Cutting

FRs of Cutting Tool Materials

FR1 = Wear Resistance

FR2 = Fracture Resistance

FR3 = Resistance to Plastic Deformation

FR4 = Stiffness

Introduction to Metal Cutting

Cutting Tool Materials

Plain carbon steel (early 1800's)

High carbon steel (mid 1800's)

High Speed Steel Tool (HSS)

Cemented tungsten carbide tools

Cemented W/Ti/Tacarbide (800 feetmin)

Aluminum oxide (>2000 ft/min)

Cubic boron nitride (CBN)

Coated tools (TiN, TiC/TiN, HfC)

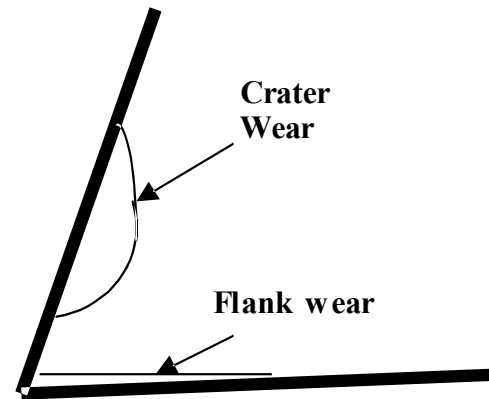
Introduction to Metal Cutting

Cutting speed increased steadily during the 20th century due to the advances in cutting tool materials.

Introduction to Metal Cutting -- Tool Wear

Crater on the rake face

Wear land formation on the “flank” face



Introduction to Metal Cutting

Tool Wear

At high cutting speed, crater wear dominates. Its wear rate is very sensitive to temperature and thus, cutting speed.

Tools fail when the crater depth is about 0.005 inches.

Introduction to Metal Cutting

Tool Wear

At low cutting speed, *flank* wear dominates.
Its wear rate is *not* sensitive to
temperature and thus, cutting speed.

When the length of the wearland reaches
about 0.030", tools fail catastrophically.

Tool Wear Mechanisms

Abrasive Wear

Delamination wear (HSS)

Solution wear

Chemical reaction

Wear due to diffusion of elements

Solution Wear

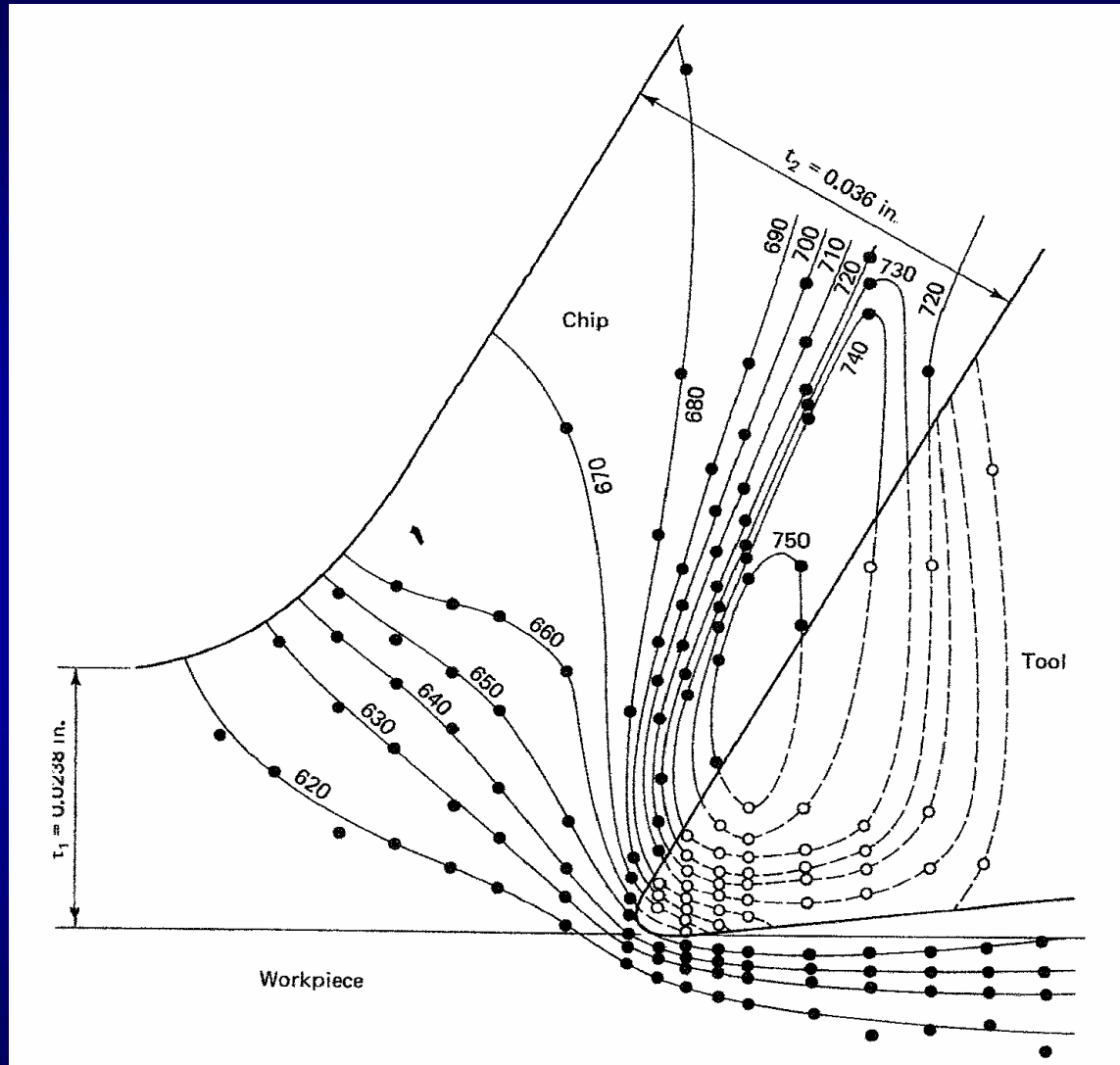
What is the definition of solution wear?

Cutting Temperature

How sensitive is the solution wear rate to temperature?

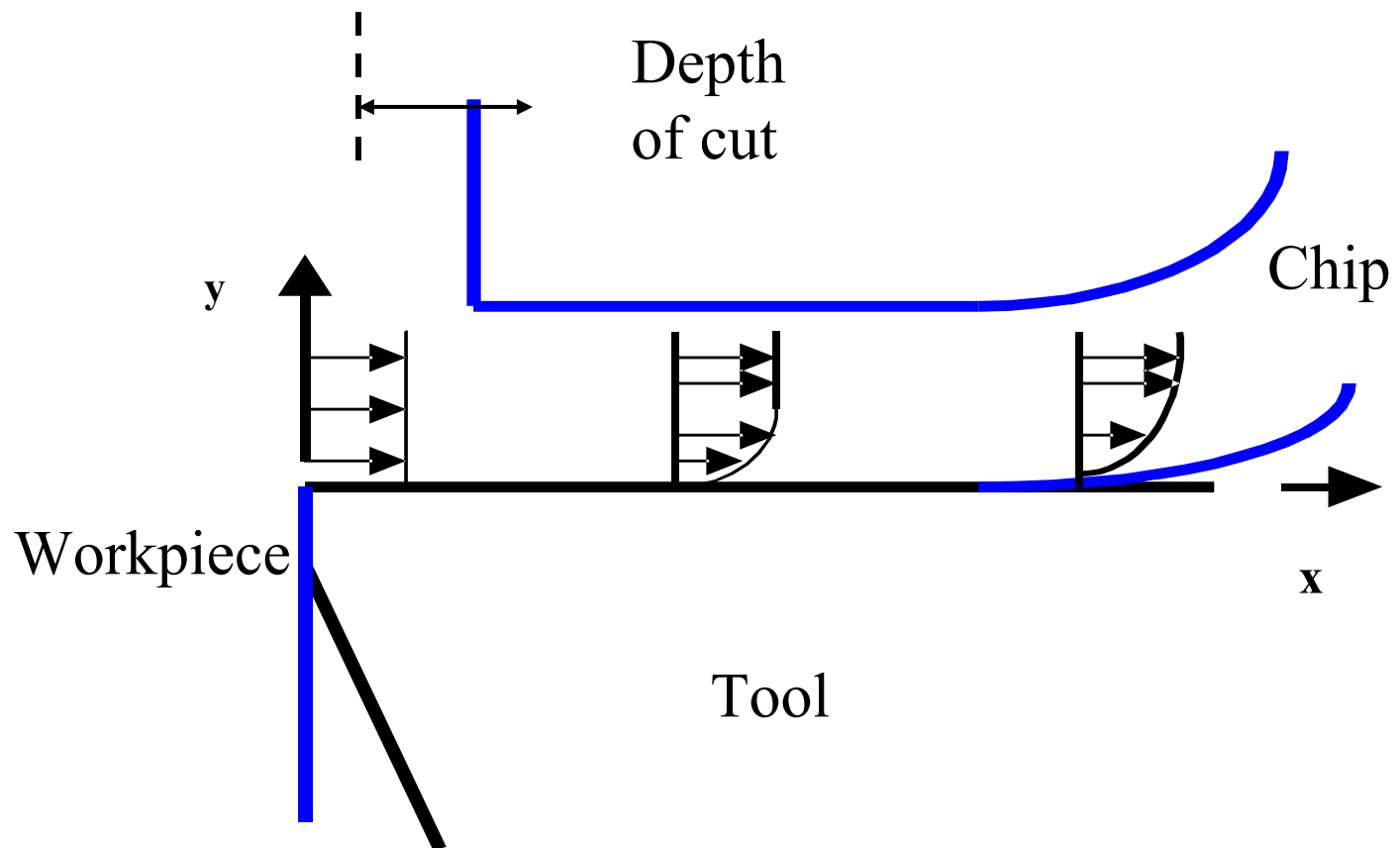
How is the maximum temperature under a typical cutting condition, e.g., cutting AISI 4340 steel at 800 ft/minute?

Cutting Temperature



Temperature distribution in cutting zone (as determined from an infrared photo). Free-cutting mild steel: speed 75 ft/min; width of cut $b=0.25$ in., rake angle $\alpha=30^\circ$, relief angle $=7^\circ$, initial workpiece temperature $T_0=611^\circ\text{C}$. (After Boothroyd, 1963).

Solution Wear



Solution Wear

Conservation of Mass

$$\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} = 0$$

Transport rate

$$\frac{1}{A} \frac{\partial m}{\partial t} = \left(cv_y - D \frac{\partial c}{\partial y} \right)_{y=0}$$

Solution Wear

Conservation of Mass

$$\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} = 0$$

Since

$$\frac{\partial v_x}{\partial x} < 0,$$

$$\frac{\partial v_y}{\partial y} > 0, \quad v_y = \text{constant} > 0$$

Solution Wear

Wear Rate of the material being dissolved

$$\frac{dV}{dt} = \int K \left(-D \frac{\partial c}{\partial y} + c_s v_y \right) dA$$

V = Wear rate of the material being dissolved

K = Ratio of the molar volumes of the tool material being dissolved and the deforming workpiece material, respectively.

D = Diffusivity of the slowest diffusing solute constituent in the material being cut

c = concentration of the dissolving material in the chip

c_s = equilibrium concentration of the tool material in chip material

Solution Wear

Wear Rate of the material being dissolved

$$\frac{dV}{dt} = \int K \left(-D \frac{\partial c}{\partial y} + c_s v_y \right) dA$$

Local Crater Wear Rate

$$v_c = Kc_s v_y$$

Relative Wear Rates of Two Different Materials

$$\frac{(v_c)_1}{(v_c)_2} = \frac{(Kc_s)_1}{(Kc_s)_2}$$

Determination of Solubility

The Gibbs Free Energy

The Gibbs Free Energy is defined as

$$G = H - TS$$

For formation of a solution at constant pressure and temperature

$$dG = 0 \quad dT = 0 \quad dP = 0$$

For an irreversible, spontaneous process at constant T and P,

$$dG < 0$$

The Gibbs Free Energy

$$G = H - TS$$

The physical significance of the Gibbs free energy :

It is the maximum useful work that can be done by a system at constant pressure and temperature.

Equilibrium Concentration c_s

At equilibrium, the change in free energy of compound ij at the chip/tool interface is equal to

$$\Delta G_{ij} = \Delta \bar{G}_i + \Delta \bar{G}_j$$

where

$$\Delta \bar{G}_i = \left(\frac{\partial G}{\partial n_i} \right)_{T, P, n_j}$$

$$\Delta \bar{G}_j = \left(\frac{\partial G}{\partial n_j} \right)_{T, P, n_i}$$

ΔG_{ij} = free energy of formation of the compound ij (i.e., tool material)

$\Delta \bar{G}_i = \Delta(\partial G / \partial n_i)_{T,P,n_j}$ = relative partial molar free energy of the solution due to the change in the amount of components i in the solvent material (i.e., chip)

μ_i = chemical potential of component i = $\Delta(\partial G / \partial n_i)_{T,P,n_j}$

Equilibrium concentration c_s

$$\Delta \bar{G}_i = \left(\frac{\partial G}{\partial n_i} \right)_{T,P,n_j} = \text{Partial molar Gibbs free energy}$$

$$= (\mu_i)_{T,P,n_j} = \text{chemical potential of component } i$$

$$\Delta \bar{G}_j = \left(\frac{\partial G}{\partial n_j} \right)_{T,P,n_i}$$

Equilibrium concentration c_s

The relative partial molar free energy of solution of component i can be expressed in terms of the relative partial molar excess free energy of solution

$$\Delta \bar{G}_i = \Delta \bar{G}_i^{xs} + RT \ln c_i$$

Equilibrium concentration c_s

Substituting these relationships into the equilibrium equation

$$\ln c_i + \ln c_j = \frac{1}{RT} (\Delta G_{ij} + \Delta \bar{G}_i + \Delta \bar{G}_j)$$

$$c_i = \exp \left[\frac{1}{2RT} (\Delta G_{ij} + \Delta \bar{G}_i + \Delta \bar{G}_j) \right]$$

Estimated and Reported Solubilities of Potential Tool Materials in α -Fe at 1600 K.

Potential Tool Material	Free Energy of Formation (cal/mol)	Estimated Equilibrium Concentration (solubility)	Exptl. Results Extrapolated to 1600 K
ZrO ₂	-190,300 ^b	3.60×10^{-8}	
Al ₂ O ₃	-278,300 ^b	5.55×10^{-7}	
Ti ₂ O ₃	-260,800 ^b	8.22	
TiO ₂	-156,300 ^b	1.52×10^{-6}	
TiO	-91,020 ^c	1.40×10^{-5}	
HfN	-52,604 ^c	1.53×10^{-4}	
HfC	-49,122 ^d	1.97	
ZrH	-51,356 ^c	2.93	
TiC _{0.75} O _{0.25}	-52,395 ^c	5.42	
ZrC	-42,714 ^d	8.42	
TiN	-45,150 ^d	1.04×10^{-3}	
TaC	-34,604 ^d	1.41	2.1×10^{-3}
TiC (iron)	-39,520 ^d	1.86	6.1×10^{-3}
NbC	-32,236 ^d	2.01	6.8×10^{-3}
BN (graphitic)	-26,100 ^f	9.65	
WC	-8,144 ^d	—	2.6×10^{-2}
VC	-23,416 ^d	—	3.2×10^{-2}
TiC (nickel)	-39,520 ^d	2.24×10^{-2}	6.3×10^{-2}
Diamond	—	9.30	
Si ₃ N ₄	-51,850 ^b	9.50	
β -SiC	-14,548 ^b	4.30×10^{-1}	

Predicted Relative Solution Wear Rates of Potential Steel-Cutting Materials at 1300 K (After Kramer, 1979).

Potential Tool Material	Predicted Relative Solution Wear Rate [$v_{\text{wear}}(\text{HfC}) = 1$]	Estimated Time for 25 μm of Wear
ZrO ₂	0.0000367	26 months
Al ₂ O ₃	0.00124	23 days
Ti ₂ O ₃	0.00245	12 days
TiO ₂	0.00313	9.1 days
TiO	0.0333	21 hr
HfN	0.680	60 min
HfC	1.	41 min
ZrN	1.56	26 min
TiC _{0.75} O _{0.25}	2.86	14 min
TiN	5.92	6.9 min
ZrC	6.20	6.6 min
TaC	9.98	4.1 min
TiC (iron)	12.8	3.2 min
NbC	15.6	2.6 min
BN	57.0	43 sec
WC	332	7.4 sec
VC	381	6.5 sec
Diamond	445	5.5 sec
TiC (nickel)	998	2.5 sec
Si ₃ N ₄	5,440	0.45 sec
β -SiC	10,700	0.23 sec

Solubilities of the Carbides in the Iron-Group
Metals at 1523 K

Carbide	Solubility [wt % (mol %)]		
	Cobalt	Nickel	Iron
WC	22 (7.9)	12 (3.9)	7 (2.2)
TiC	1 (1.0)	5 (4.9)	<0.5 (<0.5)
VC	6 (5.6)	7 (6.6)	3 (2.7)
NbC	5 (2.9)	3 (1.7)	1 (0.53)
TaC	3 (.93)	5 (1.6)	0.5 (0.15)

Comparison of Theoretical Predictions with Test Results: Predicted Relative Wear Rates at Various Temperatures

$$[V_{\text{wear}}(\text{HfC}) = 1]$$

Carbide	Temperature				Test Result
	1600 K	1500 K	1400 K	1300 K	
HfC	1	1	1	1	1
TiC	7.65	8.82	10.6	12.8	2.75
TiC _{0.75} O _{0.25}	2.26	2.41	2.61	2.86	—
ZrC	4.44	4.87	5.47	6.20	5.51
TaC	6.33 (9.43)	7.19 (10.7)	8.39 (12.5)	9.98 (14.9)	10.6
NbC	9.13 (31.0)	10.6 (36.0)	12.7 (43.1)	15.6 (52.8)	23.7
VC	(107.)	(153.)	(215.)	(332.)	(237.)

Terms without parentheses are calculated on the basis of solubility estimated from thermodynamic properties. Terms in parentheses are calculated using the reported solubilities.

Coating Techniques

- Chemical vapor deposition
- Physical vapor deposition

Melting Point of Refractory Carbides and Oxides

Carbides	T_m (°F)	Oxides	T_m (°F)	Nitrides	T_m (°F)
WC	5030	V ₂ O ₃	3578	HfN	5990
Al ₄ C ₃	4900 ± 100	TiO ₂ (brookite)	3340 ± 30	TaN	5590
VC	4950 ± 150	Al ₂ O ₃	3720 ± 40	ZrN	5400
NbC	6330 ± 135	MgO	5117 ± 35	TiN	5310
TaC	7080 ± 100	ZrO ₂	5010 ± 150	NbN	3720
ZrC	6225 ± 40	HfO ₂	5140 ± 90	VN	3720
TiC	5550 ± 30	NbO	3533	CrN	2730
HfC	7100 ± 100	—	—	—	—

Hardness of Oxides

Hardness at Specified Temperatures of the Phases
That May Be Present in a Steel

Phase	Hardness, H_V (kgf/mm ²)		
	400 °C	600 °C	800 °C
Iron	45	27	10
Iron and interstitials	90	27	10
TiO	1300	1000	650
FeO	350	210	50
MgO	320	220	130
NiO	200	140	100
MnO	120	60	45
Al ₂ O ₃	1300	1000	650
SiO ₂	700	2100	300
ZrO ₂	650	400	350
TiO ₂	380	250	160
MgAl ₂ O ₄	1250	1200	1050
ZrSiO ₄	400	290	140

Hardness of Carbides

Graph removed for copyright reasons.
See Figure 9.40 in [Suh 1986].

Material Properties

- The wear resistance of various carbides agree with their free energy of formation, tungsten being the worst and hafnium being the best.

Material Properties

- Oxides have the best chemical stability. Therefore, a zirconium oxide tool should last 26 months and aluminum oxide for 23 days under a typical high speed cutting condition of steel, but they have lower melting point and hardness than carbides.

Diffusion Wear

- This happens in machining titanium with a diamond tool.
- A new stable compound such as TiC is formed on the tool face protecting the carbide tool face. The wear rate of the tool is controlled by the diffusivity of carbon.