METAL MATRIX COMPOSITES II

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Metal Matrix Composites

- Metal matrix: Al, Ti, Mg, Fe, Cu, Ni, Co
- Ceramic particles or fiber reinforcement
  - Example: Al-SiC (silicon carbide)
  - Example: Al-Al2O3 (aluminum oxide)
  - Example: WC-Co (tungsten carbide)
- High strength, high stiffness, abrasion resistance, dimensional stability, high temperature stability and toughness.

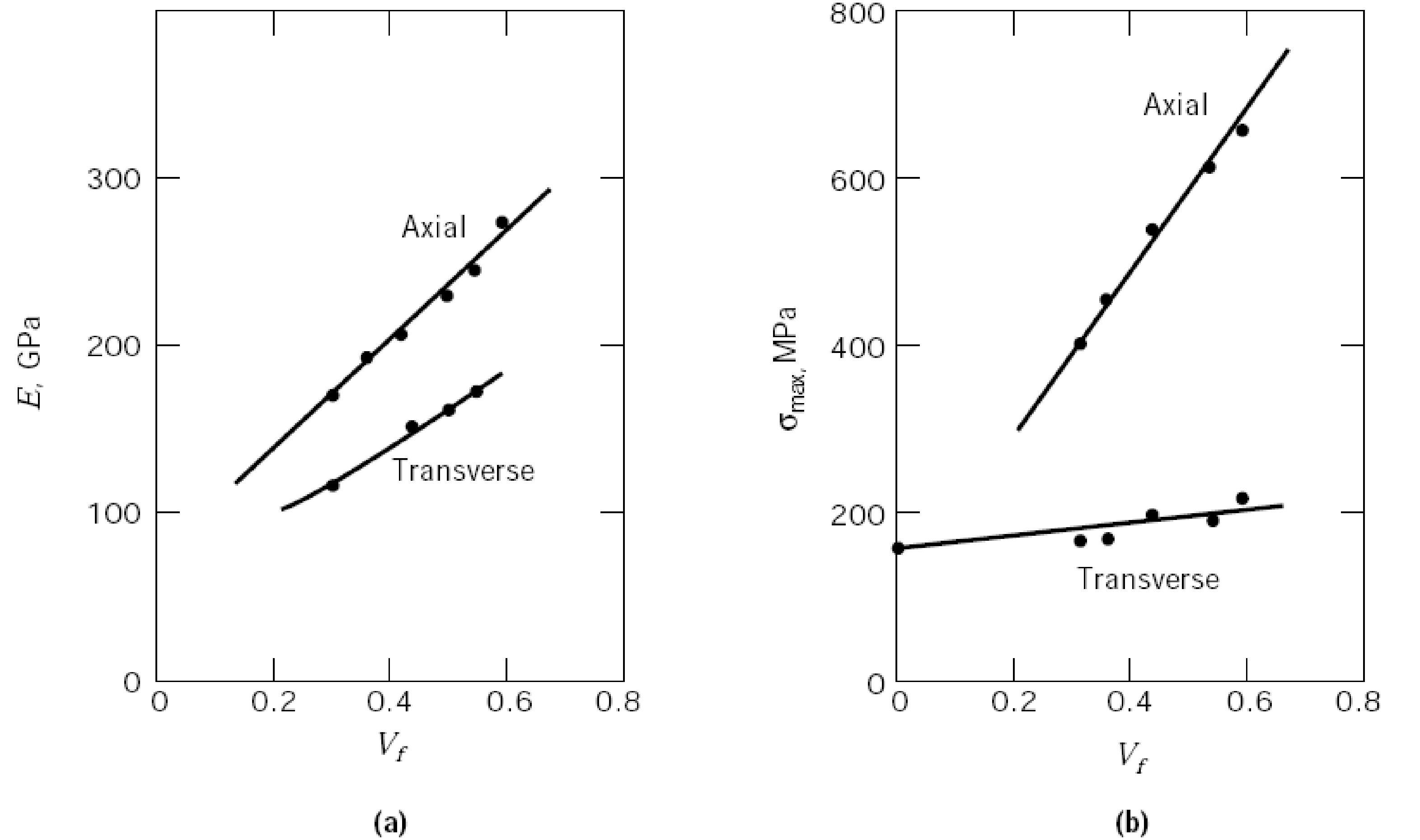
Properties of Metal Matrix Composites

- In selecting a composite material, an optimum combination of properties is usually sought, rather than one particular property
- Properties are Determined by Three Factors:
  1. The materials used as component phases in the composite
  2. The geometric shapes of the constituents and resulting structure of the composite system
  3. The manner in which the phases interact with one another

Young’s Modulus

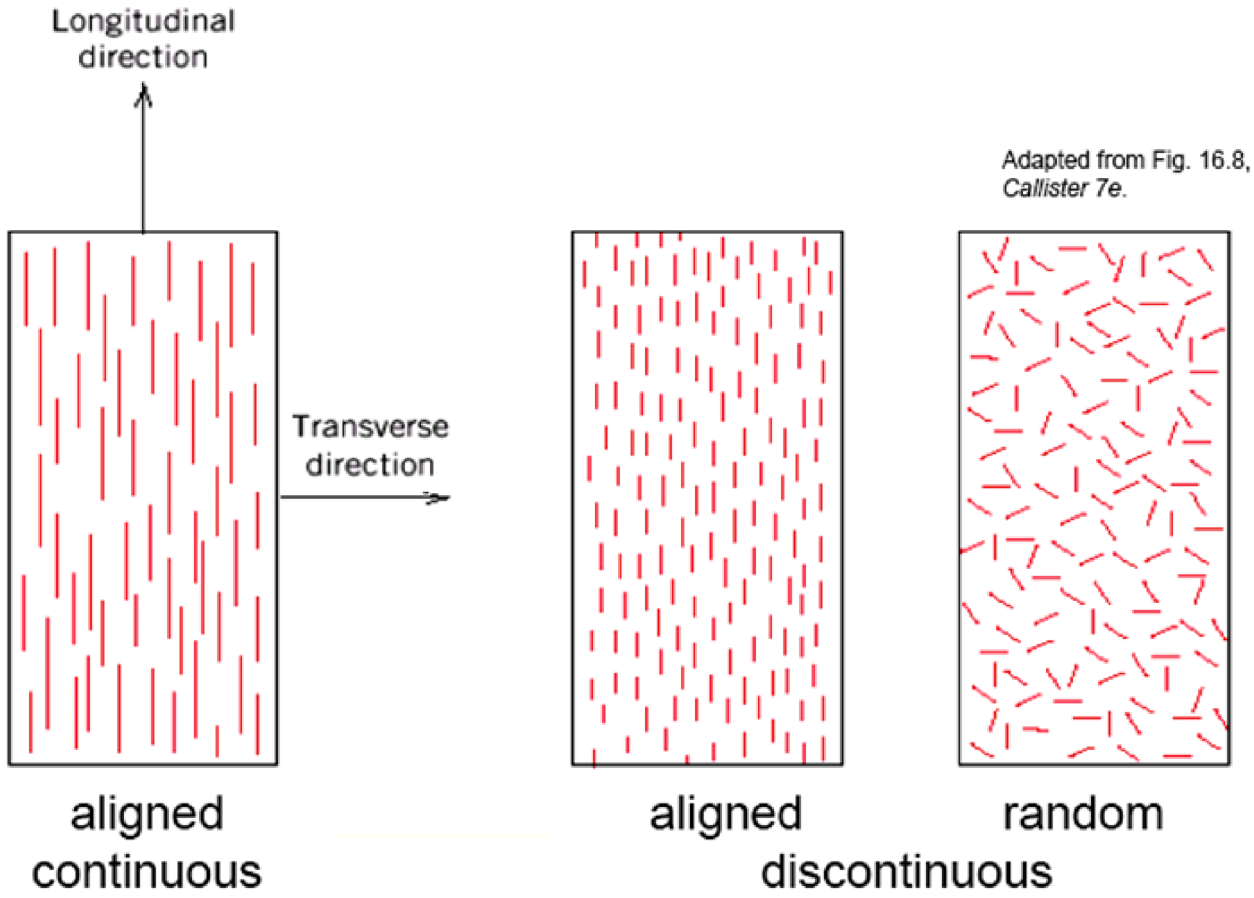
- An objective in the development of light metal composite materials is to increase the modulus of elasticity (Young’s modulus)
- Unidirectionally reinforced continuous fiber-reinforced metal-matrix composites show a linear increase in the longitudinal Young's modulus as a function of fiber volume fraction.
- The increase in the longitudinal Young's modulus is significant whereas the modulus increase in a direction transverse to the fibers is much lower.
- Particle reinforcement also results in an increase in the modulus of the composite; the increase, however, is lower
- Metal-matrix particulate composites such as SiC particle-reinforced aluminum can offer a 50−100% increase in modulus over that of unreinforced aluminum

Young's Modulus



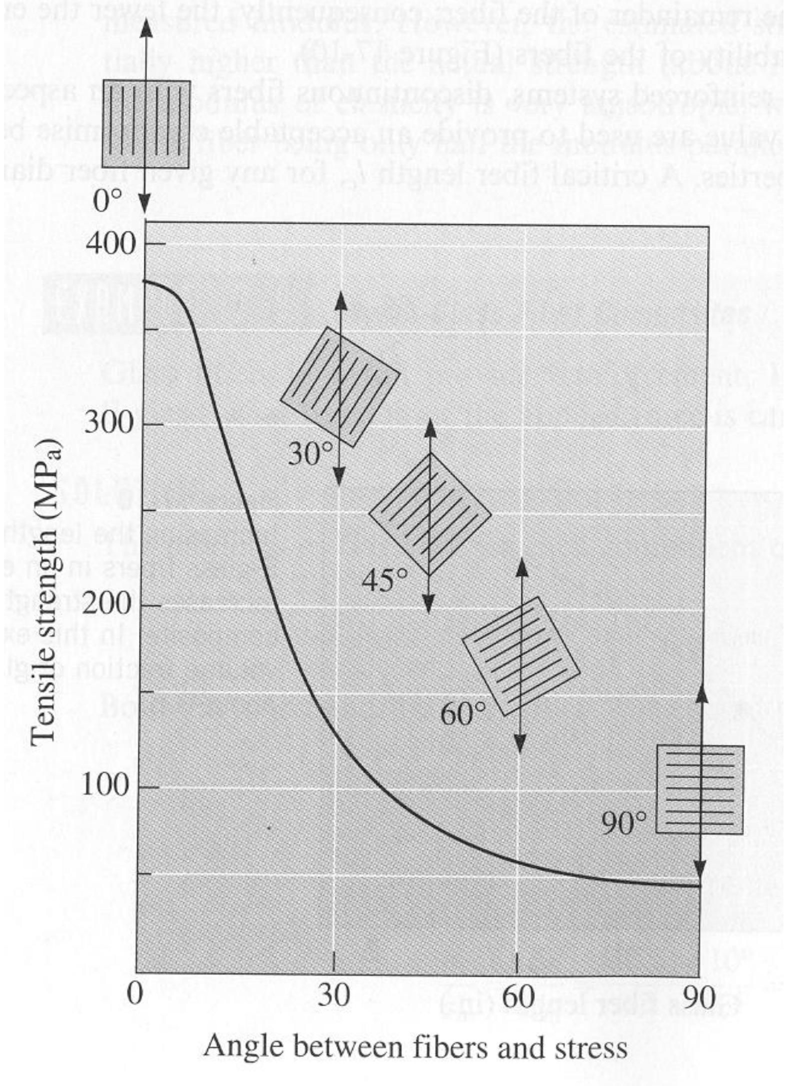
Modulus increase as a function of fiber volume fraction *Vf* for alumina fiber-reinforced aluminum–lithium alloy matrix for (**a**) *E* (elastic modulus), and (**b**) Strength

Young’s Modulus



Effect of Fiber Orientation

Maximum elastic modulus and strength is obtained when continous fibers are oriented parallel to the applied load.



Strength and Stifness

- The stiffnesses and strengths of particulate-reinforced MMCs are significantly better than those of the metal matrix.
- For example, at a volume fraction of 40 percent silicon carbide particulate reinforcement, the strength is about 65 percent greater than that of the 6061.
- High values of specific strength and specific stiffness (strength and stiffness divided by density) are desirable for high-strength, low-weight applications such as aircraft structures. Typically, particulate MMCs have somewhat better specific strength and specific stiffness than the matrix metal, and fiber-reinforced MMCs have much better specific strength and specific stiffness than the matrix metal.

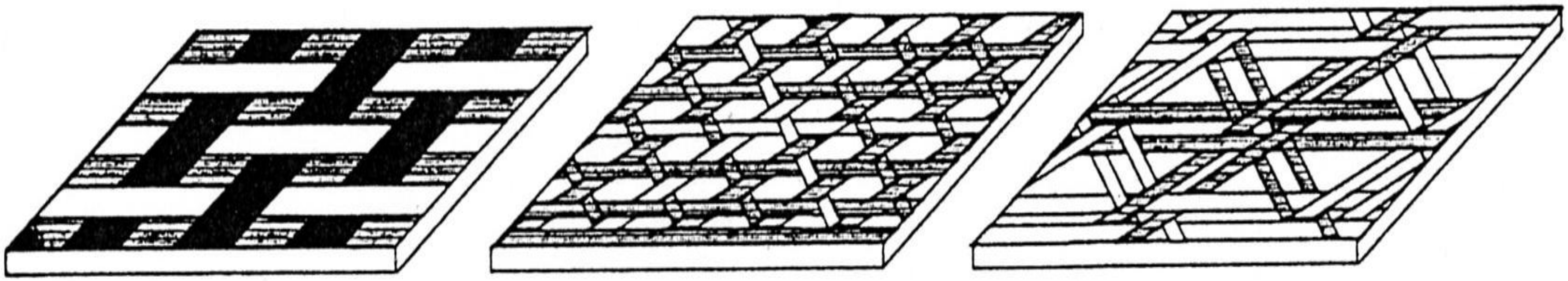
Toughness

- Toughness can be regarded as a measure of energy absorbed in the process of fracture or more specifically as the resistance to crack propagation.
- The toughness of MMCs depends on matrix alloy composition, microstructure; reinforcement type, size, and orientation; and processing as it affects microstructural variables, e.g., distribution of reinforcement, porosity, segregation, etc.
- For a given *Vf*, the larger the diameter of the fiber, the tougher the composite. This is because the larger the fiber diameter for a given fiber volume fraction, the larger the amount of tough, metallic matrix in the interfiber (interphase) region that can undergo plastic deformation and thus contribute to the toughness.

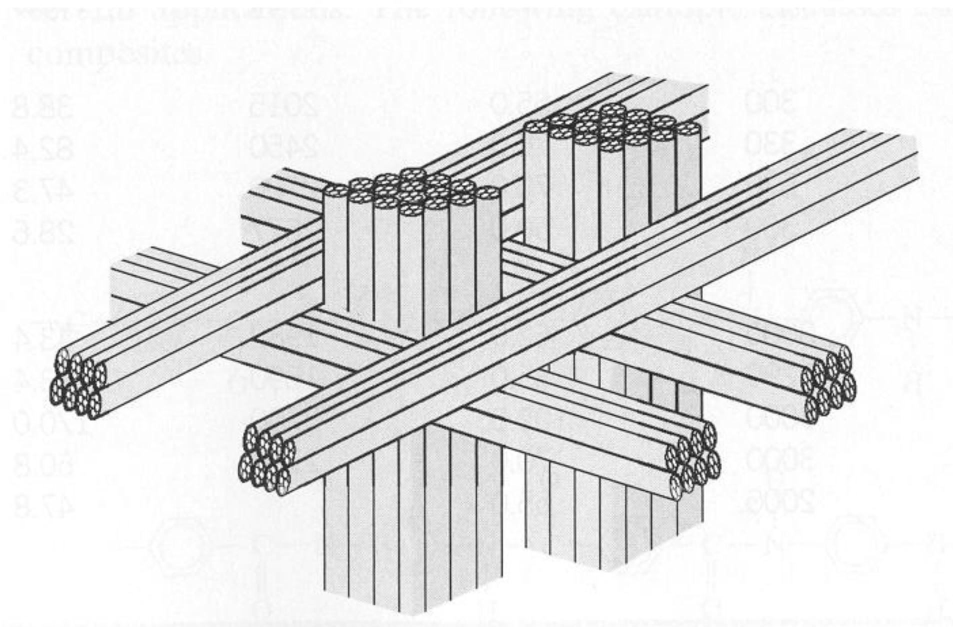
Toughness

- Unidirectional fiber reinforcement can lead to easy crack initiation and propagation compared to the unreinforced alloy matrix.
- Braiding of fibers can make the crack propagation toughness increase tremendously because of extensive matrix deformation.
- For example, the fracture energy is the maximum for a composite consisting of three-dimensionally arranged alumina fibers in an aluminum matrix.

Toughness



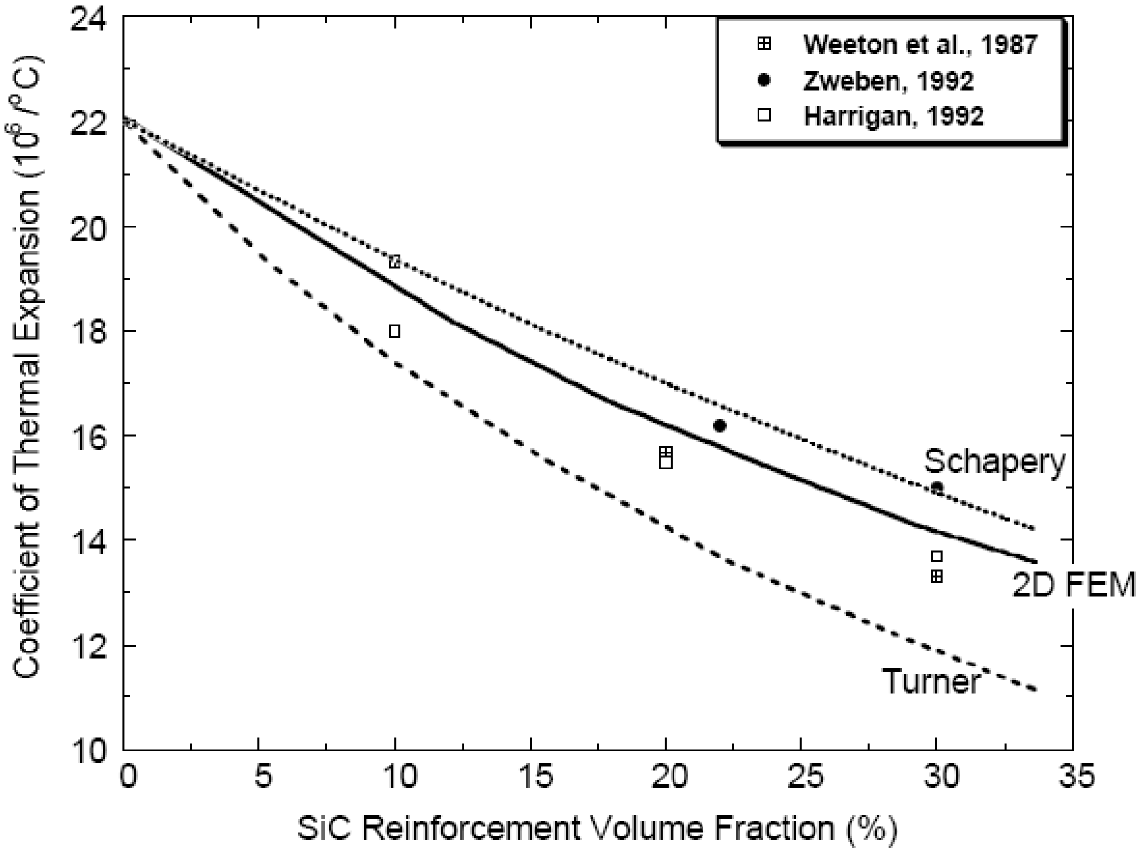
plain weave tri-axial weave bi-plane weave



Thermal and Electrical Properties

- Reinforcement of light metal alloys with ceramic fibers or particles entails a reduction in the thermal expansion coefficients and electrical conductivity.
- In general, ceramic reinforcements (fibers, whiskers, or particles) have a coefficient of thermal expansion and elecrical conductivity lower than that of most metallic matrices.
- The overall thermal expansion characteristics and electricalconductivity of a composite can be controlled by controlling the proportion of reinforcement and matrix and the distribution of the reinforcement in the matrix.
- Large coefficients of thermal expansion and thermal and electric conductivities of metals can be reduced, by the addition of fibers

Thermal and Electrical Properties

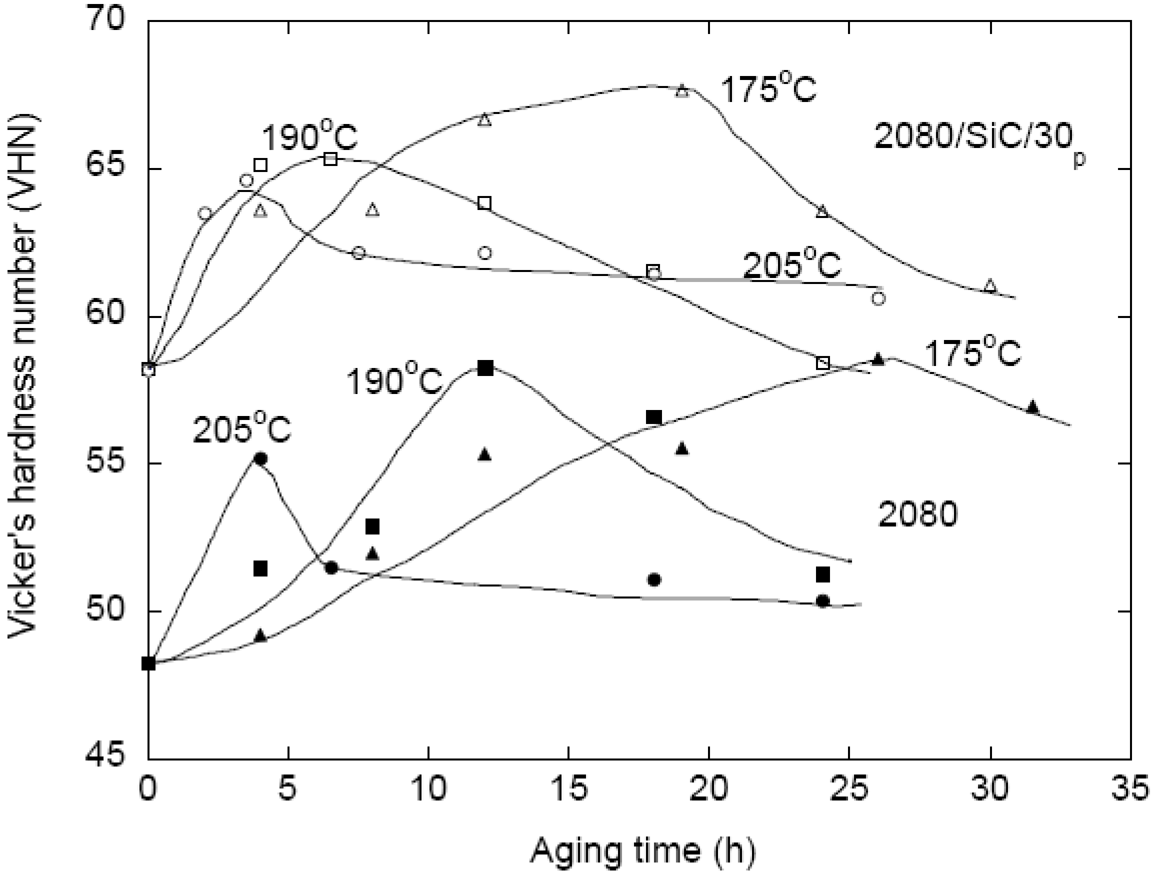


Experimental measurements and theoretical and numerical model predictions of thermal expansion behavior of a particulate MMC

Aging

- Frequently the metal-matrix alloy used in an MMC has precipitation hardening characteristics, i.e., such an alloy can be hardened by suitable heat treatment called aging.
- It has been shown that the microstructure of the metallic matrix is modified by the presence of ceramic reinforcement. In particular, a higher dislocation density in the matrix metal or alloy than that in the unreinforced metal or alloy is produced.
- The higher dislocation density in the matrix has its origin in the thermal mismatch, $\Delta\alpha$, between the reinforcement and the metallic matrix.
- A considerable strength increment results due to age hardening treatments in MMC's.

Aging

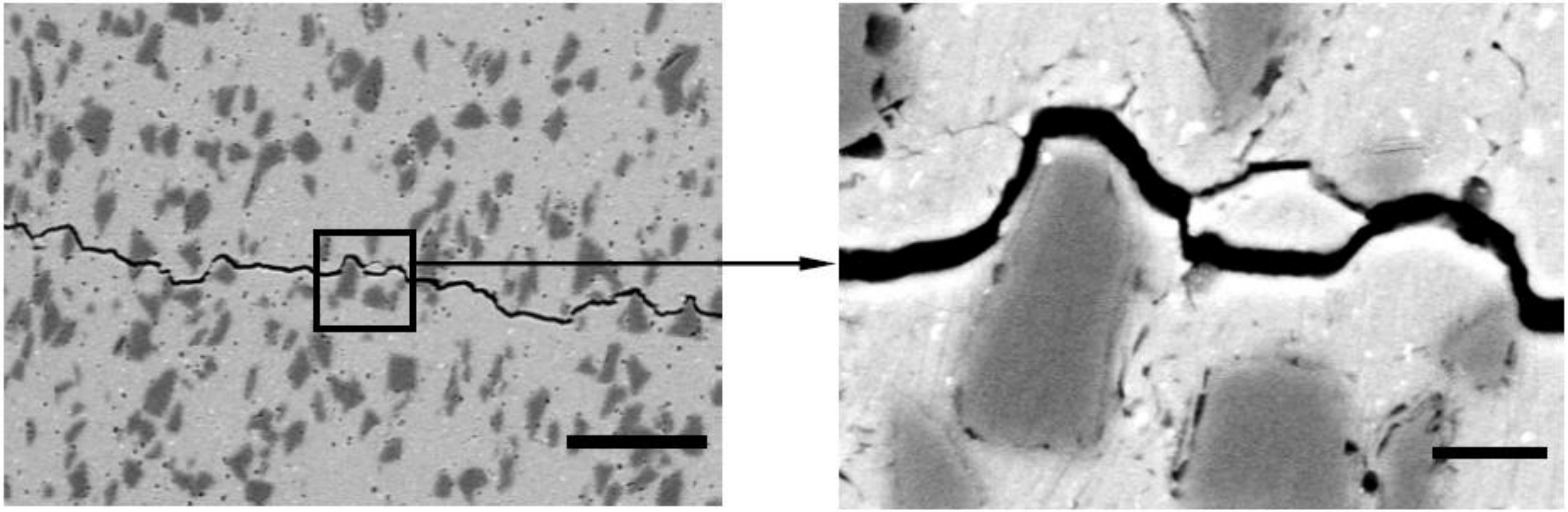


Behavior of a particle reinforced MMC versus the unreinforced matrix alloy.

Fatigue

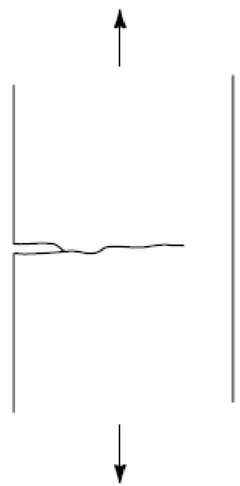
- This is the phenomenon of mechanical property degradation leading to failure of a material or a component under cyclic loading. Many high volume applications of composite materials involve cycling loading situations, e.g., automobile components.
- Processing-related defects in the form of intermetallic inclusions or particle clusters play an important role as fatigue crack initiating sites.
- These defects act as stress concentrators that increase the local stress intensity in the material and promote easy crack nucleation.
- For a given inclusion size, the stress concentration in a composite where the inclusion is surrounded by high stiffness reinforcement particles, is lower than in the unreinforced alloy.
- Since more of the load is being carried by the high stiffness ceramic particles in the composite, an inclusion will be subjected to lower stress than a similar inclusion in the unreinforced alloy.

Fatigue Crack and Fracture Thoughness

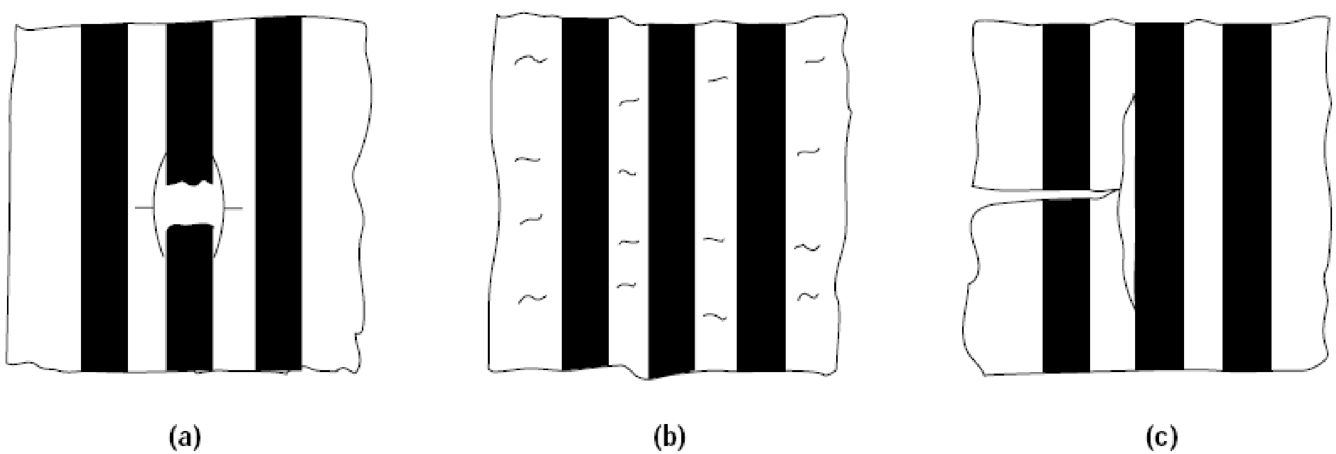


Fatigue crack growth profile in a SiC particle reinforced Al matrix composite, exhibiting crack trapping and crack deflection mechanisms.

Fatigue Crack and Fracture Thoughness



Self-similar crack propagation in an isotropic material. The crack propagates in a direction perpendicular to the cyclic loading axis

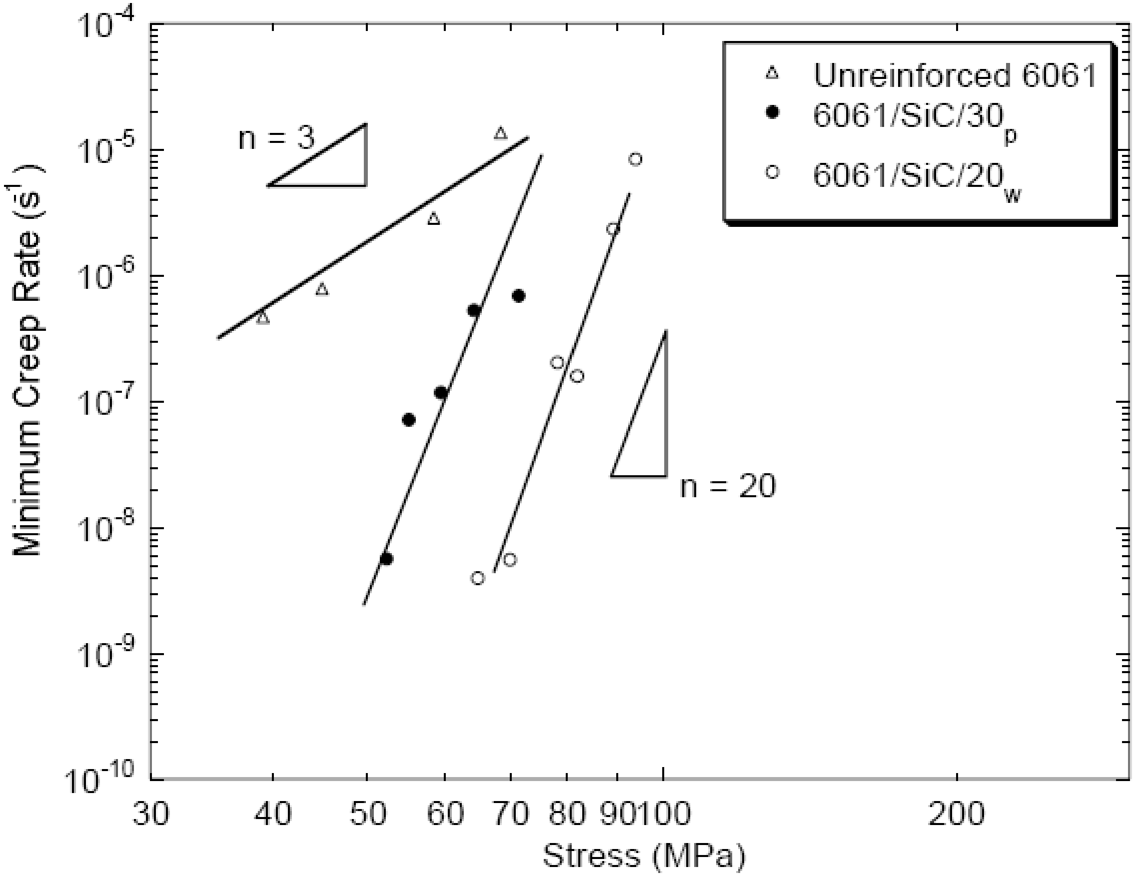


Variety of subcritical damage mechanisms in fiber-reinforced composites, that lead to a highly diffuse damage zone. (**a**) Fiber cracking, (**b**) matrix cracking, and (**c**) interface debonding.

Creep

- The phenomenon of creep refers to time-dependent deformation. In practice, at least for most metals and ceramics, the creep behavior becomes important at high temperatures and thus sets a limit on the maximum application temperature.
- In general, the creep resistance of metal is improved by the incorporation of ceramic fiber reinforcements.
- Whisker or particle reinforcement also results in significant creep strengthening over the unreinforced alloy.

Creep



Steady-state creep rate as a function of applied stress for SiC particle and SiC whisker reinforced Al matrix composites.

MMC Examples & Applications

- Dispersion Strengthened MMC's
- MMC's for Electrical Contacts
- Boron Fiber Reinforced Al Composites
- Thoria Dispersed Nickel (TD-Ni) Composites
- Cermets – Cemented Carbides
- Aerospace Applications
- Military Applications
- Transportation
- Medical Applications

Dispersion Strengthened MMC's

- These composites have little or no interaction between the two components and the particulate reinforcement is not soluble in the metal matrix.
- The dispersoids are usually 10-250 nm diameter oxide particles and are introduced by physical means rather than chemical precipitation.
- They are located within the grains and at grain boundaries but are not coherent with the matrix as in precipitation hardening
- The dispersed particles are sufficiently small in size to impede dislocation movement and thus improve yield strength as well as stiffness.

Dispersion Strengthened MMC’s

Dispersion Composites	Applications
Ag - CdO	Electrcal contacts
Al - Al_2O_3	Nuclear reactors
Be - BeO	Aerospace and nuclear reactors
Co - ThO_2, Y_2O_3	Creep resistant magnetic materials
Ni-20Cr -ThO_2	Turbine engine components
Pb - PbO	Battery grids
Pt - ThO_2	Filaments, electrical components
W - ThO_2, ZrO_2	Filaments, heaters

MMC's for Electical Contacts

- The highly conductive metals such as Cu and Ag are soft and thus show excessive wear when used in switches and relays resulting in arcing and poor contact.
- Ag reinforced with W particles has reasonable conductivity with excellent wear properties.
- The composite is made in two stages:
  - A low density W compact with interconnected pores is first produced by pressing and firing tungsten powders.
  - Liquid silver is then infiltrated into the connected voids under vacuum
- The continuous matrix of solidified Ag provides good conductivity while the continuous particles of W gives the required wear resistance.

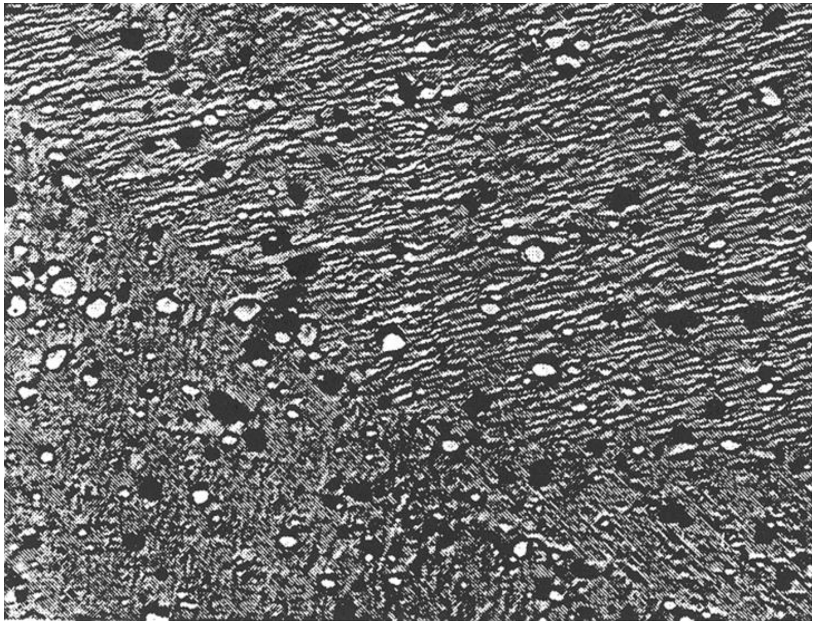
Boron Fiber Reinforced Al Composites

- Boron fibers are used to stiffen Al alloys for aircraft structures and fan blades because B has a density of 2.36 g/cm3 compared to 2.7 g/cm3 for Al and a Young's modulus of 380 GPa compared to 69 GPa for Al.
- To improve the bond with the Al matrix, the B fibers are coated with SiC, which is the origin of the trade name Borsic used for the fibers.

Thoria Dispersed Nickel (TD-Ni) Composites

- Powders of metallic Th and Ni are ball milled, compacted at high pressure and then sintered.
- The compact is then heated in air and oxygen diffuses in to react with Th metal to form a fine dispersion of ThO2.
- Thoria dispersed nickel finds its applications in various high temperature operations like combustion engines because it is a good creep resistant material. It can also be used for hydrogen trapping

Electron micrograph of Th-Ni with 300 nm diameter ThO_2 particles



Cermets

MMC with *ceramic* contained in a *metallic matrix*

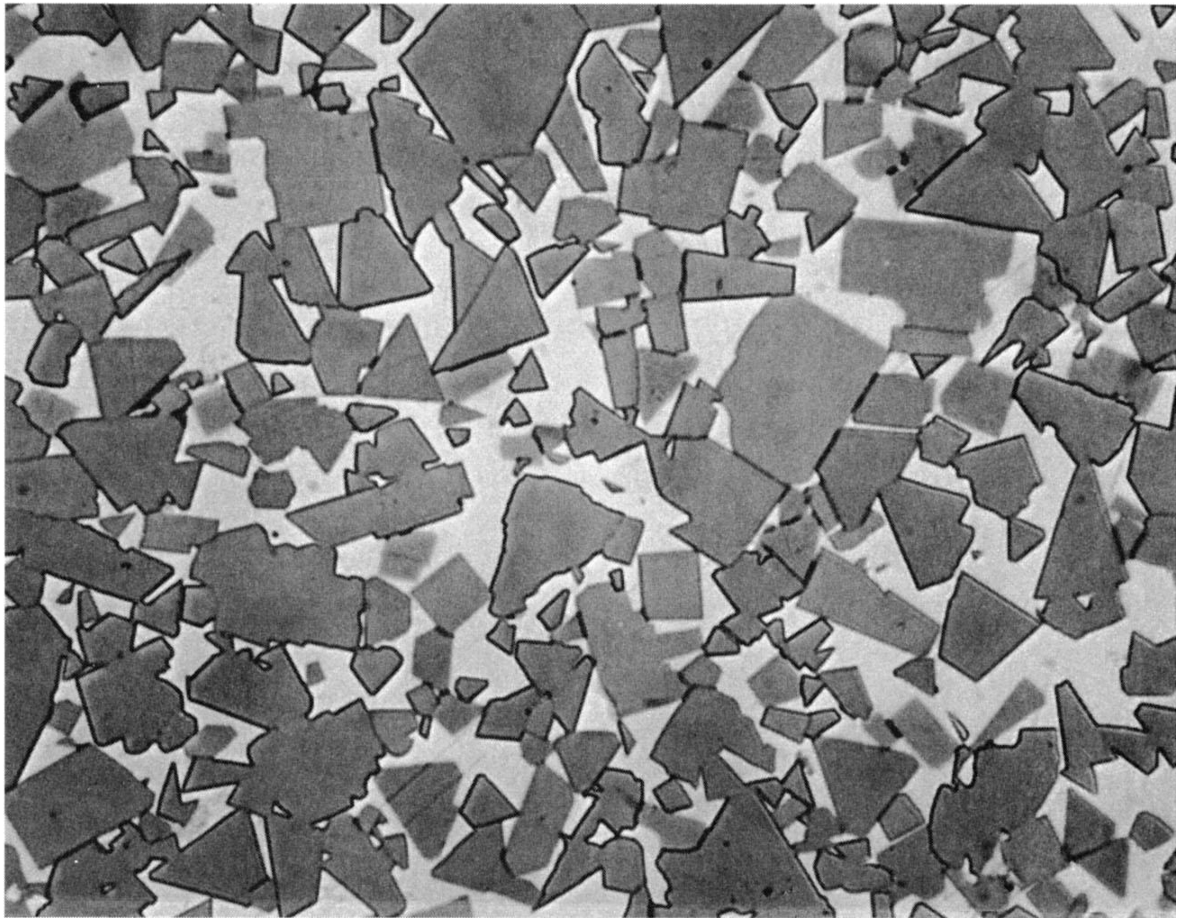
- The ceramic often dominates the mixture, sometimes up to 96% by volume
- Bonding can be enhanced by slight solubility between phases at elevated temperatures used in processing
- Cermets can be subdivided into
  1. Cemented carbides – most common
  2. Oxide-based cermets – less common

Cemented Carbides

One or more *carbide* compounds bonded in a *metallic matrix*

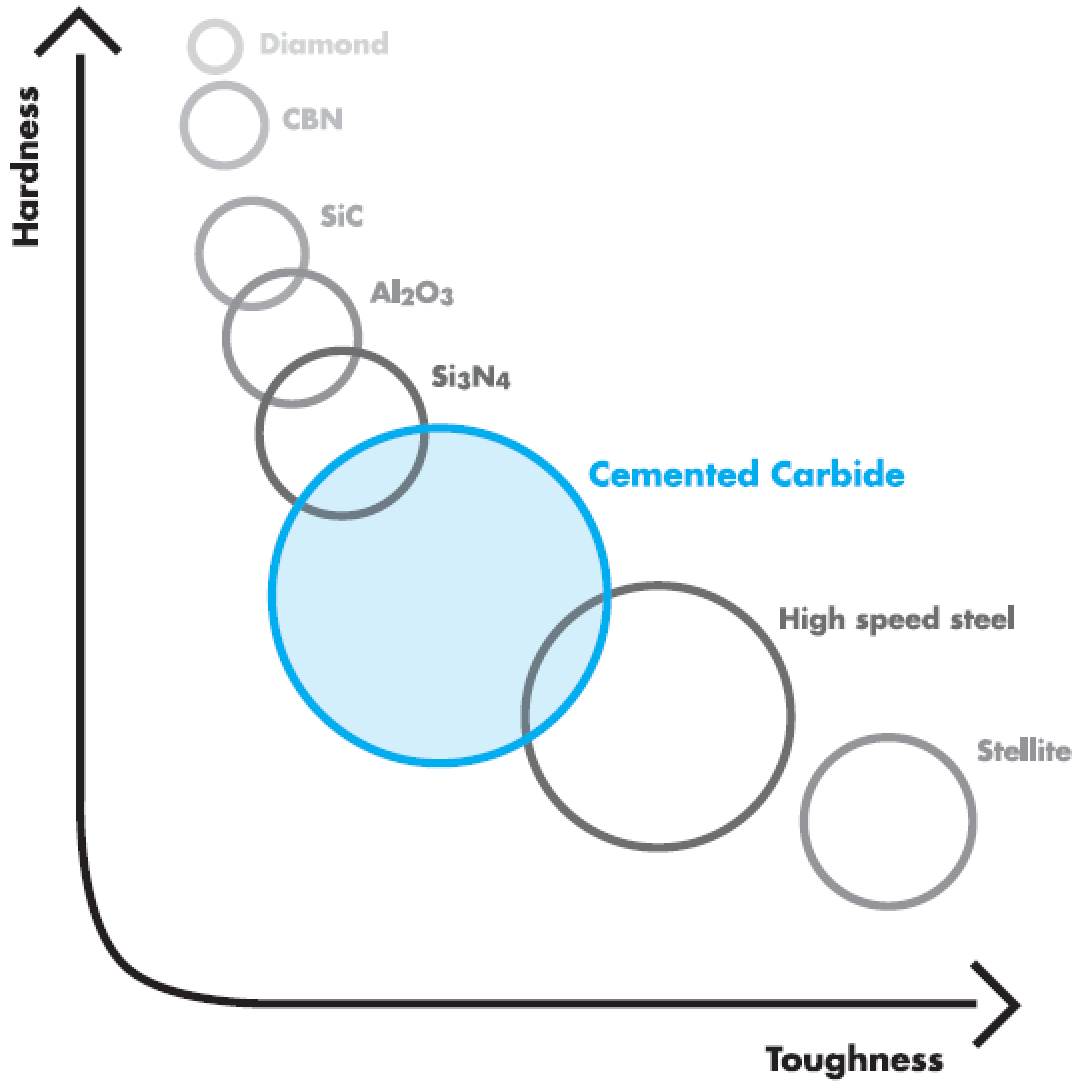
- The term *cermet* is not used for all of these materials, even though it is technically correct
- Common cemented carbides are based on tungsten carbide (WC), titanium carbide (TiC), and chromium carbide (Cr_3C_2)
- Tantalum carbide (TaC) and others are less common
- Metallic binders: usually cobalt (Co) or nickel (Ni)

Cemented Carbides

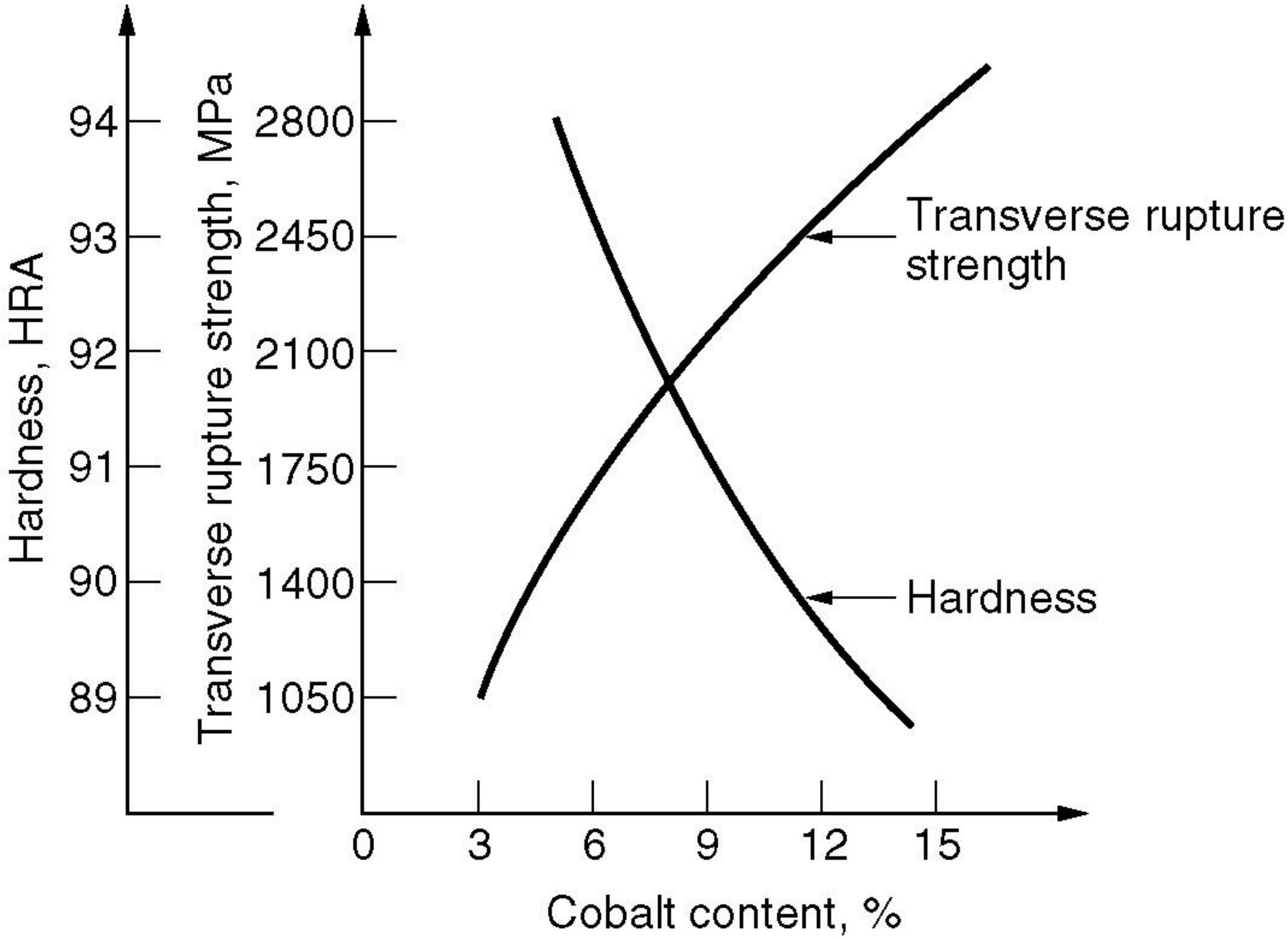


Micrograph (about 1500X) of cemented carbide with 85% WC and 15% Co

Cemented Carbides



Cemented Carbides



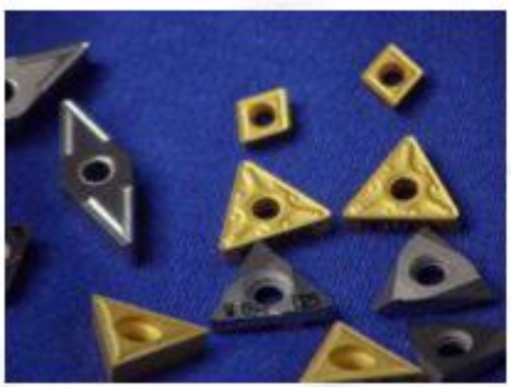
Typical plot of hardness and transverse rupture strength as a function of cobalt content

Cemented Carbides

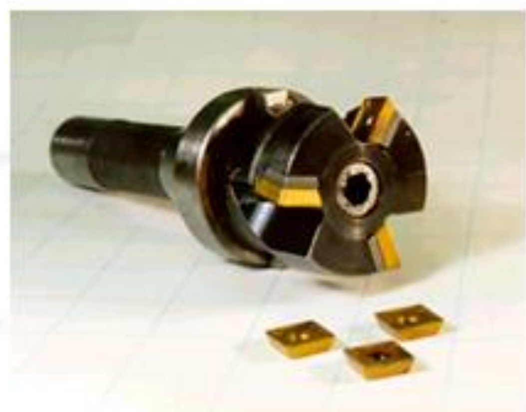
- Hard
- Wear-resistant
- Capable of maintaining a red hardness during machining operation
  - Red hardness: ability of cutting tool to maintain sharp cutting edge even when turns red because of high heat during cutting
- Able to withstand shock during cutting
- Shaped so edge can penetrate work

Applications of Cemented Carbides

- *Tungsten carbide* cermets (Co binder) - cutting tools are most common; other: wire drawing dies, rock drilling bits and other mining tools, dies for powder metallurgy, indenters for hardness testers



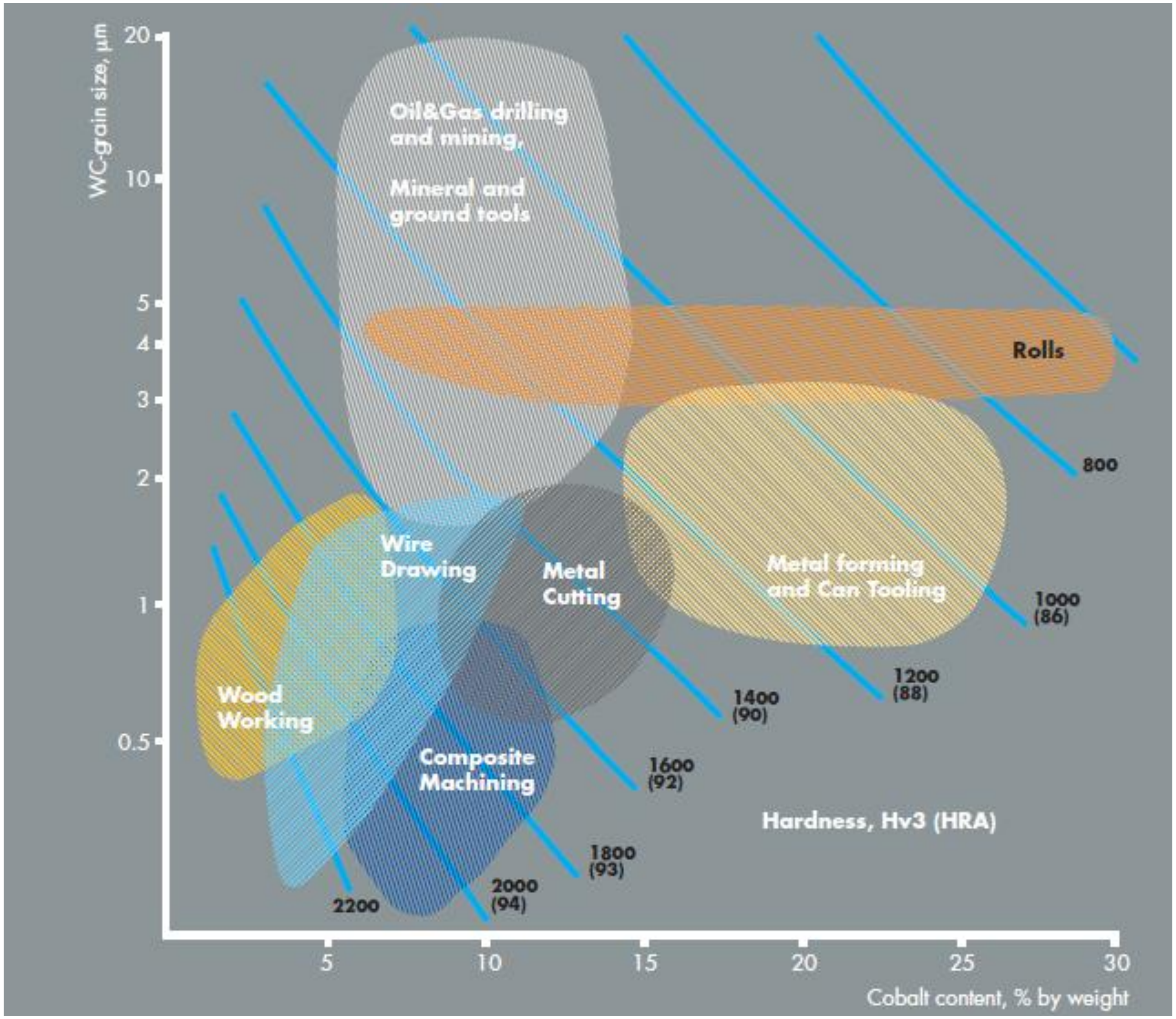
Cutting tool inserts



milling tool

lathe tool

Applications of Cemented Carbides



Applications of Cemented Carbides

- *Titanium carbide* cermets (Ni binder) - high temperature applications such as gas-turbine nozzle vanes, valve seats, thermocouple protection tubes, torch tips, cutting tools for steels
- *Chromium carbides* cermets (Ni binder) - gage blocks, valve liners, spray nozzles, bearing seal rings

Aerospace Applications

- In aerospace applications, low density coupled with other desirable features, such as tailored thermal expansion and conductivity, high stiffness and strength, are the main drivers. Performance rather than cost is the driving force for materials development.
- As continuous fiber-reinforced MMCs deliver superior performance to particle-reinforced composites, the former are frequently used in aerospace applications.
- Reduction in the weight of a component is a significant driving force for any application in the aerospace field. For example, in the Hubble telescope, a pitch-based continuous carbon fiber-reinforced aluminum was used for waveguides because of its light weight; high elastic modulus, E; and low coefficient of thermal expansion, α.

Aerospace Applications

- Copper-based composites having Nb, Ta, or Cr as the second phase in a discontinuous form are of interest for certain applications requiring high thermal conductivity and high strength, e.g., in high heat flux applications in rocket engine thrust chambers.
- Carbon fiber-reinforced copper has applications in the aerospace industry as a very high thermal conductivity material.

Military Applications

- Precision components of missile guidance systems demand dimensional stability — that is, the geometries of the components cannot change during use. Metal matrix composites such as SiC/aluminum composites satisfy this requirement because they have high yield strength. In addition, the volume fraction of SiC can be varied to have a coefficient of thermal expansion compatible with other parts of the system assembly.
- Other military applications of MMCs involve replacement of light but toxic beryllium. For example, in the United States Trident missile, beryllium has been replaced by a SiC/Al composite.

Transportation Applications

- An important application of MMCs in the automotive area is in diesel piston crowns. This application involves incorporation of short fibers of alumina or alumina−silica in the crown of the piston.
- The conventional diesel engine piston has an Al−Si casting alloy with a crown made of a nickel cast iron.
- The replacement of the nickel cast iron by aluminum matrix composite results in a lighter, more abrasion resistant, and cheaper product.
- Another application in the automotive sector involves the use of carbon fiber and alumina particles in an aluminum matrix for use as cylinder liners in the Prelude model of Honda Motor Co.

Transportation Applications

- Particulate metal-matrix composites, especially with light metal-matrix composites such as aluminum and magnesium, also find applications in automotive and sporting goods.
- In this regard, the price per kg becomes the driving force for application.
- An excellent example involves the use of Duralcan particulate MMCs to make mountain bicycles.
- A Specialized Bicycle company in the Unites States sells these bicycles with the frame made from extruded tubes of 6061 aluminum containing about 10% alumina particles. The primary advantage is the gain in stiffness.
- An important item in this regard has to do with recycling and reclamation, particularly in aluminum matrix composites, because recycling has been extremely successful in the aluminum industry.

Medical Applications

- Niobium–titanium superconductors are used in magnetic resonance imaging (MRI) techniques for medical diagnostics.