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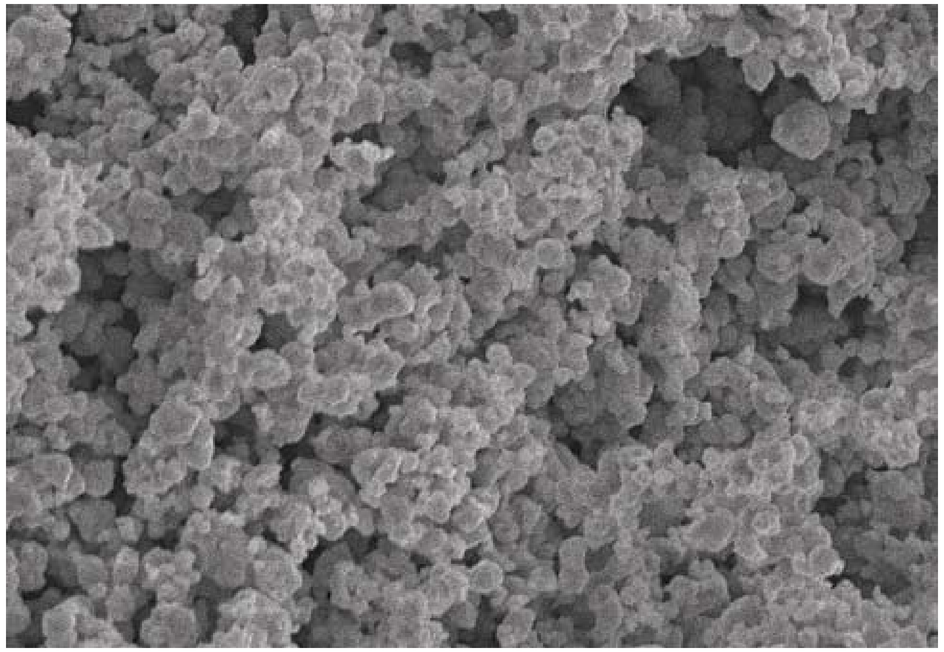
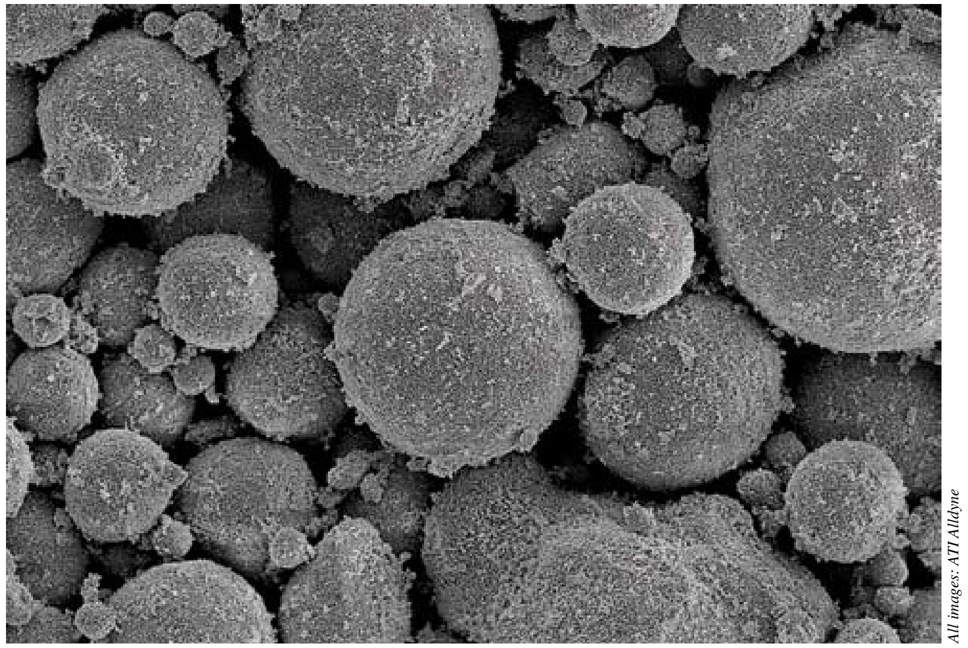
Powder POWER

Knowing the basics of tungsten carbide grades, including their characteristics as cutting tool materials, can help parts manufacturers choose the right tool for an application.





All images: ATI Alldyne

Scanning electron microscope images of a WC powder after carburization (left) and a graded WC powder after spray drying.

Cemented carbides, also known as hardmetals, are the most widely used class of materials for high-speed machining (HSM). They are produced by powder metallurgy and consist of hard carbide particles, usually tungsten carbide (WC), in a ductile metal binder. There are hundreds of different WC-based combinations. The majority of them utilize cobalt (Co) as the binder, but nickel (Ni) and chromium (Cr) are also used. Other alloying elements may be added as well. Why are there so many grades and how does a toolmaker select the right material for a given application? To answer these questions, let's first review what makes cemented carbides desirable as cutting tool materials.

Hardness and Toughness

WC-Co has a unique combination of hardness and toughness. WC by itself is very hard, surpassing corundum, or aluminum oxide, in hardness and loses little hardness at elevated working temperatures. However, it lacks sufficient toughness to function as a cutting tool. To utilize WC's high hardness and improve its toughness, it is coupled with a metallic binder. This provides a material that is considerably harder than HSS while being tough enough to withstand the forces encountered in most cutting applications. It can also withstand the high temperatures of HSM.

Today, almost all WC-Co tools and inserts are coated, so the role of the substrate may seem less important. However, it is the high elastic modulus—a measure of stiffness—of WC-Co at cutting temperatures (about three times HSS's room-temperature elastic modulus) that provides a nondeforming base for the coating. The substrate also provides needed toughness. These properties are fundamental to WC-Co, but can be tailored through compositional and microstructural adjustments during processing of the powder. Thus, the suitability of a tool's properties to a specific application depends in large part on the starting powder.

Powder Production

WC powders are produced by carburizing tungsten (W) powders. The characteristics—especially the particle size—of the WC powder depend primarily on the starting W particle size and the carburization temperature and time. Chemistry control is also critical. The carbon content must be held constant near its stoichiometric value of 6.13 percent by weight. Small amounts of vanadium and/or chromium can be added prior to carburization to control the grain size through later processing steps. Different downstream processing conditions and different end-use applications require specific combinations of WC particle size, carbon content, vanadium content and chromium content. Permutations of these combinations result in a high number of WC powders. For example, ATI Alldyne produces 23 standard WC powders and five times that on a custom basis.

Many more combinations are possible when the WC powders are milled with a metal binder to produce a "graded" powder. Co is most commonly used in contents of 3 to 25 percent by weight, but Ni and Cr are used in applications that require enhanced corrosion resistance. The metal binder can be further modified through additional alloying. For example, adding ruthenium to WC-Co significantly increases its toughness without decreasing hardness. Increasing the binder content also increases toughness, but at the expense of hardness.

A smaller WC particle size can increase hardness, but grain size must be preserved during the sintering process. During sintering, the WC particles bond and grow through a solution-reprecipitation process. The metallic binder becomes liquid during the actual sintering process (known as liquid-phase sintering) to provide a material that is fully dense. The rate of WC grain growth can be controlled by additions of other transition metal carbides, including vanadium carbide (VC), chromium carbide (Cr_3C_2), titanium carbide (TiC), tantalum carbide (TaC) and niobium carbide (NbC). They are generally added when the WC powder is milled with the metal binder, although VC and Cr_3C_2 can also be formed during the carburization of the WC powder.

Graded WC powders can also be produced from recycled scrap material via a zinc-reclaim process or by crushing. These "reclaimed" powders often provide more predictable compaction behavior because they have less surface area than WC powders made directly from the carburization of W. Recycling scrap material is an important part of the overall economics of the WC industry. Tungsten can be chemically extracted from practically all waste streams containing it and reprocessed into WC powders with the same properties and quality as if they were made from ore.

Conditions for milling the WC powder with the metal binder are also key processing parameters. Two common milling techniques are ball milling and attritor milling. Both processes homogenize the mixture and can reduce particle size. An organic binder is usually added during milling to later provide sufficient strength in pressed parts to hold their shape and allow handling by operators or robots. The organic binder's chemical composition can affect the density and strength of pressed parts. A high strength binder is desirable for handling, but results in a lower pressed density and can produce hard agglomerates that can cause defects in the final product.

After milling, the powders are usually spray dried to produce free-flowing agglomerates held together by the organic binder. The flowability and packing density of the agglomerates can be tailored by adjusting the organic binder's composition. The agglomerates' size distribution can be further tailored by screening out coarse or fine fractions to insure good flowability for filling die cavities.

Part Production

Carbide parts are fabricated by a number of methods. Due to their size, level of shape complexity and manufactured quantities, most cutting inserts are pressed in a rigid die with top and bottom punches. The same amount of powder in terms of both mass and volume must flow into the die cavity for each pressing to maintain uniform part weight and size. Powder flowability is mostly controlled by the agglomerate size distribution and the

Methods of recycling

The tungsten industry has a long history of recycling scrap material from all types of waste streams. Recycling scrap helps control material costs, preserves natural resources and eliminates the need to dispose of waste material in landfills. ATI Alldyne recycles tungsten-carbide scrap using the APT (ammonium paratungstate) process or the zinc-reclaim process. More information on the tungsten recycling process is available in a special Interactive Report at www.ctemag.com, or visit the ATI Alldyne Web site at www.alldyne.com or call the ATI Alldyne scrap hotline at (256) 722-2259.

organic binder's properties. Compaction pressures of 10 to 80 ksi are applied to the powder to form the pressed, or "green," part.

Even at these pressures, the hard WC particles do not deform or fracture, but the organic binder is forced into the interstices between the particles, helping to lock them into place. Higher compaction pressures bring the WC particles closer together, increasing the part's pressed, or green, density. The pressing characteristics of graded WC powders can vary depending on metal binder content, particle size and shape, degree of agglomeration, and composition and amount of organic binder. Plots of green density vs. compaction pressure are often constructed by the powder producer to provide quantitative information on the pressing characteristics of graded WC powders. This information ensures that the powder will be compatible with the toolmaker's compaction process.

Green (left), sintered (middle) and coated (right) inserts show the dimensional change from green to sintered WC.

Large carbide parts or those with high aspect ratios, such as rods for endmills and drills, are often manufactured by isostatically pressing graded WC powder in a flexible bag. Production cycles are longer than for die compaction, but the tooling cost is lower, making isopressing more suited for lower volume production.

In this process, the powder is poured into the bag, the end of the bag is sealed off, and the powder-filled bag is placed in a chamber, which is pressurized to 30 to 60 ksi with a hydraulic fluid. The pressed part is often machined to a specific geometry before being sintered. The bag is oversized to accommodate part shrinkage during consolidation and to provide adequate stock for grinding.

Because the parts are machined afterward, uniform powder packing is not as critical as for die compaction, but it is still desired to ensure that the bag is filled with the same amount of powder each time. If the powder has a low packing density, the bag may be filled with insufficient powder, resulting in undersized parts that have to be scrapped. If the powder has a high packing density, the bag may be filled with excess powder, requiring more powder to be machined away after pressing. Although this powder is recycled along with that from any scrapped parts, it reduces process efficiency.

Carbide parts can also be produced by extrusion or injection molding. Extrusion is better suited to high-volume axisymmetric parts, while injection molding is used for producing complex geometries in high volumes. In both processes, the graded powder is suspended in an organic binder, which gives the mixture the consistency of toothpaste. The mixture is then either extruded through an orifice or injected into a die cavity. The characteristics of the graded powder determine the optimal ratio of powder to binder in the mixture and greatly affect the mixture's flow properties through the orifice or into the die cavity.

After the part has been shaped by die compaction, isopressing, extrusion or injection molding, the organic binder is removed from the part prior to the final sintering stage. Sintering removes pores from the part, making it fully or nearly fully dense. During sintering, the metallic binder in the pressed part becomes liquid, but a combination of capillary forces and particle contacts maintains the shape of the part.

After sintering, the part has the same geometry, but is smaller. To produce a specific size part after sintering, a shrink factor is designed into the tooling. The graded powder used for each set of tooling must be designed to have the correct shrinkage when compacted at the appropriate pressure.

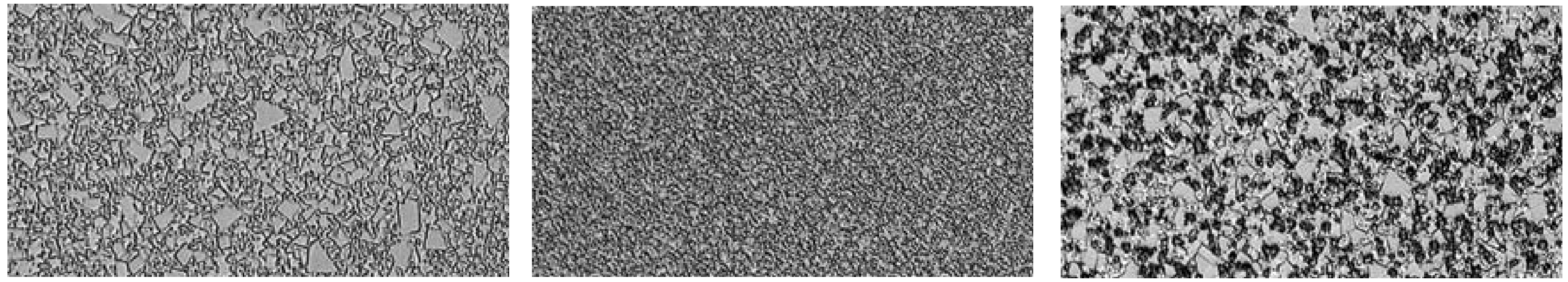
In almost all cases, the sintered parts undergo post-sintering operations. The minimum operation performed on a cutting tool is honing the cutting edge. Many tool geometries require grinding after sintering. For some tools, the top and bottom will be ground. Others require the periphery to be ground with or without honing the cutting edge. All tungsten-based grinding residue can be recycled.

Putting on a Coat

In many cases, the finished part is coated. The coating provides lubricity and increased hardness. It also provides a diffusion barrier to keep the substrate from oxidizing when exposed to high temperatures. The WC substrate is critical to coating performance. In addition to tailoring the bulk properties of the substrate powder, chemistry selection and enhanced sintering practices can tailor substrate surface properties. The outermost 20µm to 30µm of the insert can be enriched with binder relative to the rest of the part via cobalt migration to give it the performance of a tougher grade with the ability to resist deformation characteristic of the binder content below the surface layer.

Toolmakers that use graded WC powders may have specific requirements based on their processes, such as dewaxing methods, heating rates, sintering times, temperatures and carburization potential. Some toolmakers may sinter in a vacuum furnace while others use a sinterHIP furnace, which pressurizes parts at the end of the cycle to eliminate any remaining porosity. Those that sinter in a vacuum may hot isostatically press (HIP) their parts to full density in a separate cycle. Some toolmakers may use a higher vacuum sintering temperature to improve densification of compositions with lower Co contents, but this can coarsen the microstructure. To maintain a fine grain size, a powder with a smaller WC particle size can be selected. Dewax conditions and carburization potential may require a higher or lower carbon content in the starting powder to match specific production facilities.

All of these factors critically affect the microstructure and performance of the sintered carbide tool and require close communication between the toolmaker and powder supplier to ensure that the graded WC powder is tailored for the toolmaker's process. It is no surprise that there are hundreds of different possible grades. For example, ATI Alldyne produces more than 600 different graded powders. Each of these lots is engineered to work effectively for the targeted customer and application.



Sintered microstructures of a straight grade (left), a micrograin grade (center) and an alloyed grade (right), which includes cubic carbides.

Grade Types

The different types of WC powders, the composition and amount of the metal binder and the type and amount of grain growth inhibitor are responsible for the variety of cemented carbide grades. These parameters will critically determine the microstructure of the cemented carbide and its properties. Certain combinations of properties are preferred for specific applications, providing a means of categorizing multiple grades.

Two common application-oriented classification systems are the C-grade system and the ISO system. Neither system completely reflects the material properties that influence carbide grade selection, but they provide a starting point for discussion. Many manufacturers have their own specific grades for each classification, which contributes to the large variety of available grades.

Grades are also classified by composition. WC grades can be divided into three basic types: straight, micrograin and alloyed. Straight grades are primarily WC in a Co binder but may contain small amounts of grain growth inhibitors. Micrograin grades consist of WC in a Co binder with several tenths of a percent of VC and/or Cr_3C_2 to achieve a grain size of less than 1µm. Alloyed grades consist of WC in a Co binder with several percent of TiC, TaC and NbC, which are known as cubic carbides because they show up as a blocky third phase in sintered microstructures.

Straight: These grades for metalworking generally contain 3 to 12 percent Co by weight. The WC grain size usually ranges from 1µm to about 8µm. As with other grades, a smaller grain increases hardness and transverse rupture strength (TRS), but decreases toughness. Hardnesses of straight grades typically range from 89 to 93.5 HRA and TRSs range from 175 to 350 ksi. The powders for these grades may contain significant amounts of reclaimed constituents.

Straight grades can be classified as C1 to C4 in the C-grade system or under the K, N, S and H designations in the ISO system. Straight grades with intermediate properties can be classified as general-purpose grades, such as C2 or K20, and used for turning, milling, planing and boring. Harder grades with finer grain sizes or lower Co contents can be classified as precision machining grades, such as C4 or K01. Tougher grades, with coarser grain sizes or higher Co contents, can be classified as roughing grades, such as C1 or K30.

Tools made of straight grades are used to machine cast iron, 200 and 300 series stainless steels, aluminum and other nonferrous metals, high-temperature alloys and hardened steel. They are also used for nonmetalworking applications, such as rock and earth drilling tools. These grades have grain sizes ranging from 1.5µm to 10µm or more and contain 6 to 16 percent Co by weight. Another nonmetalworking application for straight grades is for dies and punches. These grades generally have a medium grain size with Co contents ranging from 16 to 30 percent by weight.

Micrograin: These grades generally contain 6 to 15 percent Co by weight. The VC and/or Cr_3C_2 additions control grain growth during liquid-phase sintering, producing a final grain size of less than 1µm. The fine grain size gives very high hardness and TRS of 500 ksi or more. High strength combined with adequate toughness enable the use of more positive rake angles, which reduce cutting forces and produce thinner chips by cutting instead of pushing metal.

Proper performance is achieved by rigorous characterization of starting raw materials in the production of the graded powder along with critical control of sintering conditions to prevent formation of abnormally large grains in the microstructure. To keep grain size small and consistent, reclaimed powders can only be used with complete control of the source material and reclaim process, as well as extensive quality checks.

Micrograin grades can be classified under the M designation in the ISO system in addition to the same C-grade and ISO designations as straight grades. They are used to produce tools for cutting soft workpieces because they can be highly polished and can hold an extremely sharp cutting edge.

Micrograin grades can also be used for machining Ni-base superalloys because of their ability to withstand temperatures up to 1,200° C. For high-temperature alloys and other exotic materials, micrograin and straight grades containing ruthenium can be used to simultaneously improve wear resistance, deformation resistance and toughness. Micrograin grades are also desired for rotating tools that generate shear stresses, such as drills. One development is composite drills with the Co content varying within the tool to optimize hardness and toughness at specific locations within a single bit.

Alloyed: These grades are primarily used for cutting steel and typically contain 5 to 10 percent Co by weight. The grain size ranges from 0.8µm to 2µm. TiC additions range from 4 to 25 percent by weight and reduce the tendency of WC to diffuse into steel chip surfaces. TaC and NbC additions up to 25 percent by weight improve strength, cratering resistance and thermal shock resistance. These cubic carbide additions also increase the hot hardness, which helps avoid thermal deformation in heavy-duty or other applications where high temperatures are created at the cutting edge. In addition, TiC provides nucleation sites during the sintering process, improving the uniform distribution of cubic carbides within the parts.

Hardnesses of alloyed grades typically range from 91 to 94 HRA and TRSs range from 150 to 300 ksi. Alloyed grades are less resistant to abrasive wear and have lower strengths than straight grades but are more resistant to adhesive wear.

The alloyed grades can be classified as C5 to C8 in the C-grade system or under the P and M designations in the ISO system. Alloyed grades with intermediate properties can be classified as general-purpose grades, such as C6 or P30, and used for turning, threading, planing and milling. The hardest grades can be classified as precision-machining grades, such as C8 or P01, and used for finish turning and boring. These formulations typically have fine grain sizes and low Co content to achieve the required hardness and wear resistance, but larger additions of cubic carbides can also achieve similar properties.

The toughest grades can be classified as roughing grades, such as C5 or P50. These formulations typically have medium grain sizes, high Co content and smaller amounts of cubic carbide to achieve required toughness by inhibiting crack propagation. Enhanced performance in interrupted turning can also be obtained by using enriched grades, which have a higher Co content at the surface as previously described.

Alloyed grades with low TiC contents are used for cutting stainless steel and ductile cast irons, but can also be used for machining nonferrous metals, such as Ni-base superalloys. They generally have grain sizes of less than 1µm and contain 8 to 12 percent Co by weight. Higher hardness grades, such as M10, are used for turning ductile cast irons, while tougher grades, such as M40, are selected for milling and planing steel or for turning stainless steels or superalloys.

Alloyed grades are also used for nonmetalworking applications, primarily as wear parts. Typical grain sizes range from 1.2µm to 2µm with Co content ranging from 7 to 10 percent by weight. These grades are commonly manufactured with a significant portion of reclaimed constituents, providing a significant cost benefit for wear applications. Wear grades for applications requiring increased corrosion resistance and higher hardness are manufactured with additions of Ni and Cr_3C_2.

Compositions, properties and typical applications for example grades.

	Co (wt.%)	TiC (wt.%)	Ta(Nb)C (wt.%)	VC (wt.%)	Cr (wt.%)	Hardness (HRA)	TRS (ksi)	Grain Size*	C Code	ISO Code(s)	Example Application
Straight grades											
	5.5	-	0.7	-	-	92.4	225	F	C4	K01	Precision turning cast iron
	6	0.17	0.34	-	-	92.0	260	F	C2	K20, N15, S10	Turning cast iron
	11	0.4	0.8	-	-	89.7	360	M	C1	K30	Rough milling cast iron
Micrograin grades											
	6	-	-	0.2	0.3	92.8	310	XF	-	M10, N05, S05	Drilling Ni-base superalloys
	10	-	-	0.3	0.5	91.9	360	XF	C8	M25, N15, S15	Turning Ti alloys
Alloyed grades											
	5.5	3	4.5	-	-	91.4	220	M	C7	P15	Finishing high-strength steels
	10	6.5	11.4	-	-	91.2	250	M	C6	P30	Milling high-strength steels
	11	5.5	3.5	-	-	90.5	220	M	C5	P45	Slotting high-strength steels

* XF=extra fine, F=fine, M=medium

The Power of Powder

Powder is the critical ingredient in meeting both the technical and financial needs of toolmakers. Powders engineered to toolmakers' process equipment and process parameters ensure final part performance and result in hundreds of grades. The recyclability of tungsten materials and the ability to work directly with powder providers enables toolmakers to control their quality and material costs. △

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