International Tungsten Industry Association

Cemented carbides – a success story

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Dummy (from IMOA Fabrication of Austhenitic Stainless Steels, © Seco Tools

Introduction

In 1923, when the well-known *Schröter patent* on cemented carbides* was submitted by the Patent-Treuhand-Gesellschaft für elektrische Glühlampen m.b.H in Berlin, Germany [1], no one, even the most optimistic, could imagine the enormous breakthrough for this material in the tooling industry.

After WW2, a huge market opened in the growing economies and cemented carbides contributed as tool materials and construction parts to their industrial development. Today, cemented carbides are the workhorses in all areas of the manufacturing industries: no factory without cemented carbide tools; no production of glass bottles, aluminium cans or plastic tubes which has not benefited from these hard and wear resistant materials; no steel or copper wire or tube drawn without them; and no advanced manufacturing system without relying on their properties, innovation potential, productivity and reliability.

Starting from the first application as drawing die for the production of lamp wire used in the OSRAM workshops (**Figure 1**), the application of cemented carbides has become universal and includes metal cutting, machining of wood, plastics, composites, soft ceramics, chipless forming (hot and cold), mining and construction, structural parts, wear parts, and military components.

Larger cemented carbide producers prepare several thousand differently shaped specimens ranging in mass between less than 1 g (such as balls for ball-point pens, which are produced to the tune of 5 billion parts a year) and some hundred kg (such as dies and pistons in the synthetic diamond industry or plungers in the plastics industry).

In 2008, roughly 50,000 tons of tungsten (W content) were consumed worldwide in cemented carbides, which account for about 60% of the world's tungsten consumption (including recycled material). In terms of tonnages, stone-working and machining of wood and plastics are the largest fields of application (26%), followed by metalcutting (22%), wear applications (17%) and chipless forming (9%); (**Figure 2**; left). In contrast, the metalcutting group accounts for 65% of the turnover (due to its high degree of innovation), compared to stone working (10%), machining of wood and plastics (10%), wear applications (10%) and chipless forming (5%); (**Figure 2**, right).

Why is this material so successful in the manufacturing industry? What are the main reasons? And, will its unique position in the industry be maintained in the near future? It is the aim of the present article, to present a series of important applications of cemented carbides and to give a few simple answers to these important questions.

* the German word *Hartmetall* was used for the new product. In direct translation to English this expression denotes *hardmetal*, a term which is also used internationally. The term *cemented carbide* was used first in the United States by researchers at General Electric/Carboloy and it much better describes the nature of the metallic composite.

Figure 1: Wire drawing dies with alternating diameter (left); production facility at Widia/Essen in the early 1930s (right). To produce drawing dies with diamond-like hardness but improved toughness was the driving force for the development of cemented carbides in the 1920s. Field tests were made in the OSRAM factories in 1923 and diamond dies were quickly replaced for the wire drawing of tungsten down to 0.3 mm. In 1925, Friedrich Krupp took over the patent rights and called the new material WIDIA (i.e. like-diamond). Until the mid 1930s, the worldwide production of cemented carbides remained in the range of ten tons per year (statement by Alfried Krupp, chairman of the Krupp AG: "my candy assembly" – referring to the large amounts of steel which was produced at the Krupp AG company in comparison to the new exotic material) [2]. Source: WIDIA-Handbuch, Essen, 1936.

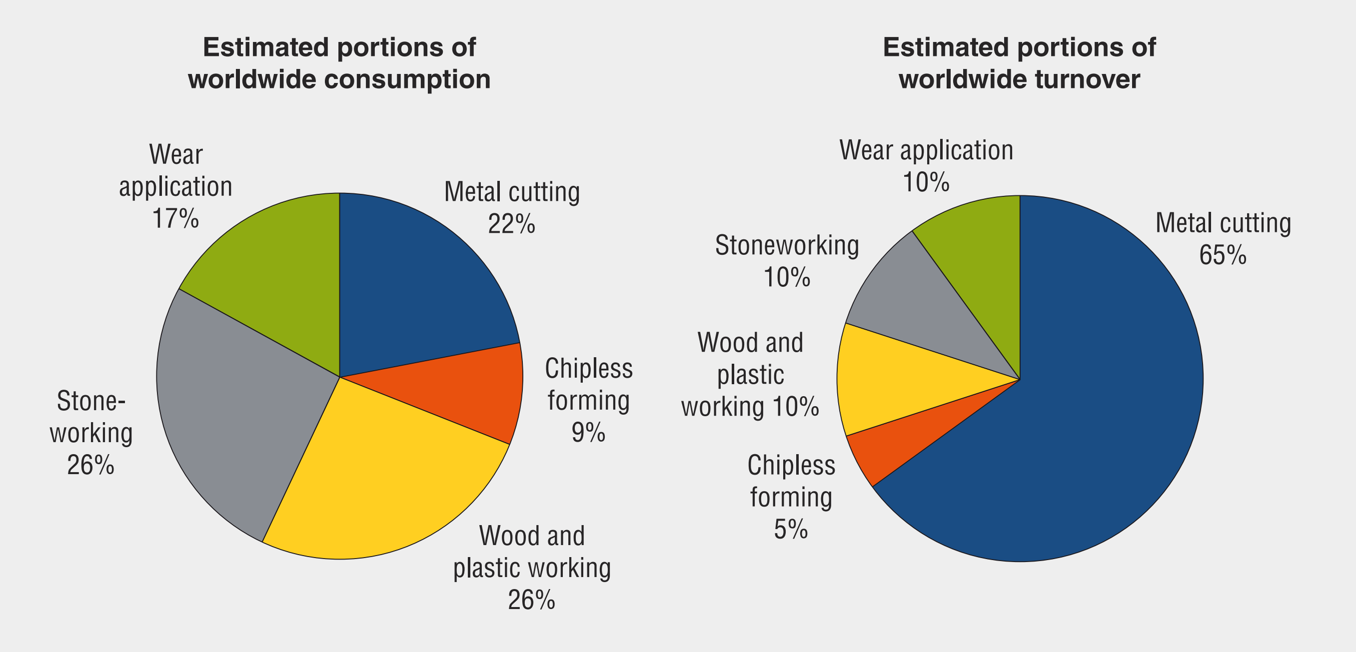
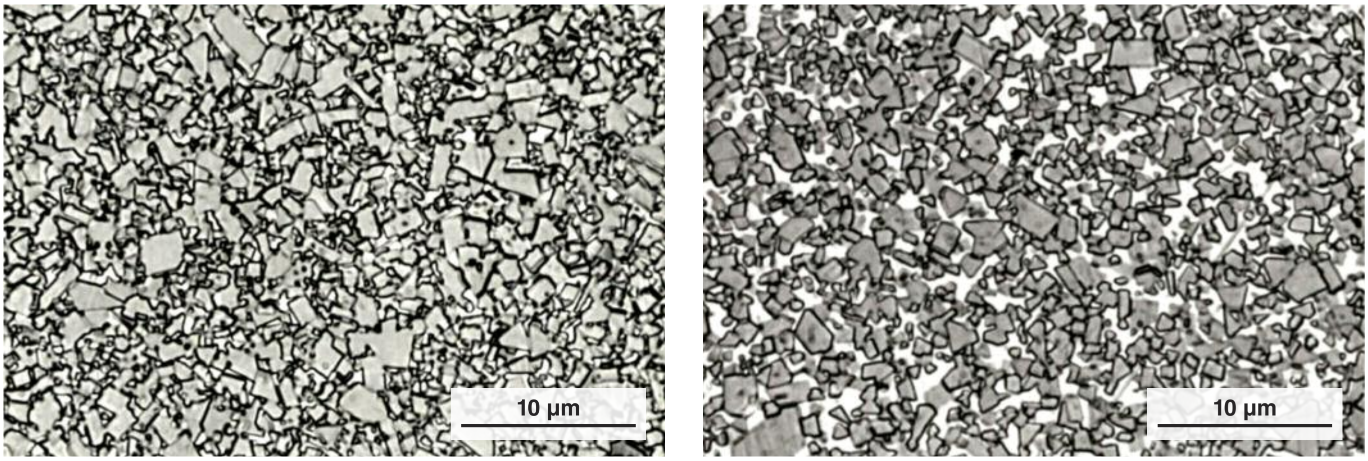


Figure 2: General application areas of cemented carbides by worldwide consumption (left) and by turnover (right) in 2010; note the significant differences in share due to the strong differences in tonnages consumed by the specific area and the degree of added value.

WC and Cobalt – a successful and reliable partnership

Cemented carbides combine the high hardness and strength of metallic carbides (WC, TiC, TaC) or carbonitrides (e.g. TiCN) with the toughness and plasticity of a metallic alloy binder (Co, Ni, Fe), in which the hard particles are evenly distributed to form a *metallic* composite (**Figure 3**). Tungsten carbide is the most metallic of the carbides, and by far the most important hard phase. The more hard carbide particles are within the material, the harder it is but the less tough it behaves during loading; and, vice versa, significant increases in toughness are achieved by a higher amount of metallic binder at the expense of hardness.



hardness: 1450 HV10; toughness: 12 MPa$\sqrt{m}$

hardness: 800 HV10; toughness: 25 MPa$\sqrt{m}$

Figure 3: Optical micrograph of two cemented carbide grades with low (6 m% Co; left) and high (20 m% Co; right) cobalt binder content, indicating the nature of the metallic composite: 1-2 μm sized hard WC particles are embedded in a tough cobalt alloy matrix; the more carbide, the harder is the material but the less tough. Typical application ranges for these two alloys: left: metal cutting, wear parts (left); cold forming tools, mining and construction (right).

This simple principle leads to an astonishingly broad band of property relationships and possible applications, which range from high-strength steels on the tough side (Vickers Hardness: about 800 HV10) to hard ceramics on the hard and wear resistant side (Vickers Hardness: 2800 HV10); (**Figure 4**). However, compared to hard ceramic materials, such as aluminium oxide or silicon carbide, which behave brittle during loading, cemented carbides always still exhibit a considerable toughness, due to the part-metallic nature of the composite.

It is this remarkable relationship between high hardness and considerable toughness, and the high flexibility of the materials in terms of property combinations which make cemented carbide tools so successful in the machining industry. A too low toughness (resistance against crack propagation) would easily result in premature material failures during working. Beyond that, even hard materials, such as hardened steel, high strength titanium alloys and ceramics or fibre-reinforced composites, can be machined at a high level of productivity.

Even today so-called straight grades (containing WC and Co only) have maintained their unique position in the tooling industry, due to their outstanding properties. Additions of other hard carbides or carbonitrides (e.g. TiC, Ti(C,N), TaC) or alternative binder materials (Ni, NiCr, FeNiCo) have widened the application range in certain directions, for example in the machining of steel (TiC, TaC) or corrosion and oxidation resistant environments (NiCr), but the two phase materials (WC-Co) still demonstrate their predominance in numerous applications.

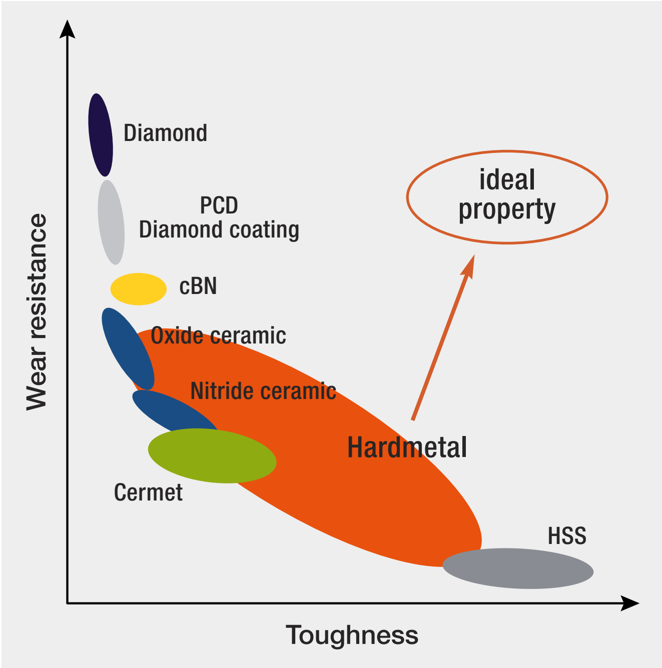


Figure 4: Schematic comparison of tool materials in terms of hardness (wear resistance) and toughness (resistance against crack propagation); note the broad range of property combinations which can be achieved by cemented carbides through tailoring the partners (WC, Co) within the composite; this range can even be extended to higher hardness by coating the materials with superhard materials (e.g. diamond) or formation of diamond/cemented carbide compacts.

PM – a flexible manufacturing process

Cemented carbides are produced by Powder Metallurgy (PM). The respective powders (WC, Co, but also other metallic carbides or carbonitrides as well as Fe and Ni) are at first ball milled or attritor milled to form a powder mix. Then, a part is formed by different shaping technologies. In the case of large lot sizes and comparatively simple geometries, as with cutting inserts or mills, the part is formed by die pressing to its final shape (*direct forming*) (**Figure 5**). Cylindrical shaped parts or parts with large length-to-diameter ratio are formed by extrusion. Plastfiers (e.g. waxes) are added prior to extrusion to render a smooth flow of the powder mix through the die. Small parts with complex geometries can be shaped by PIM (Powder Injection Moulding). In this case the plastified material is pressed into a mould, which is subsequently opened to remove the shaped part.

Large parts, such as rolls, hobs, anvils or rotary cutters for the hygiene industry are mainly produced by cold isostatic pressing (CIP). A "green" (isostatically pressed) block is formed at first, and subsequently, machined to the desired shape, either in the pressed or presintered stage to improve the strength of the still porous part (40 to 50 vol%) for the shaping; (**Figure 6**; *indirect forming*).

After shaping the materials undergo a thermal treatment, called sintering, to form a dense, near-pore free body (residual porosity commonly below 0.02 vol%). Sintering is done either in vacuum or under hydrogen. Pressure-aided sintering (sinterhip) has become a standard technology to produce defect-free materials of outstanding strength.

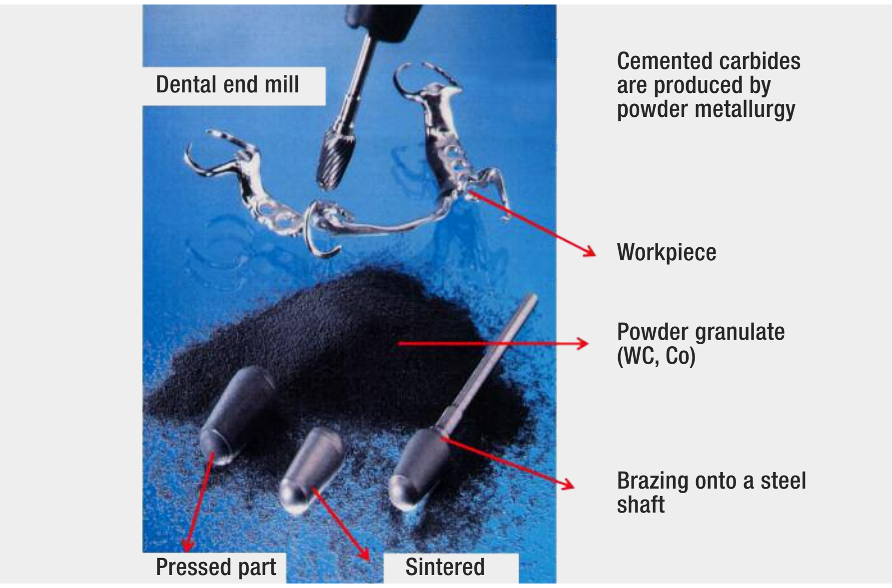


Figure 5: Dental endmill shown in different stages of manufacturing. Note the significant shrinkage which occurred on sintering; during this stage the still porous "green" part is transformed into a dense body of outstanding strength properties; the final shape of the endmill is formed by a post-sinter grinding operation with diamond tools; courtesy of CERATIZIT S.A.

During sintering, the body shrinks as a result of pore elimination (lateral shrinkage between 17 and 24%) but retains its shape. The better is the manufacturing process (milling, granulation, pressing, sintering), the more the part can be sintered to its final geometry (near-net-shape technology), and the less material has to be removed by subsequent precision grinding by diamond tools.

The result of sintering is a material with varying shape and composition (depending on the respective formulation for subsequent application), outstanding strength properties, high hardness, and high modulus of elasticity at a still considerable toughness level.

Figure 6: Rod mill roll in the different stages of manufacturing (indirect forming). At first a cylindrical part is formed by cold isostatic pressing (upper image); the part is then formed in the "green" stage by turning with diamond tools (below); after sintering and precision grinding the roll is used worldwide for high-speed finishing blocks in steel works for the hot rolling of steel rod and wire (to the right); typical cemented carbide: extra coarse grain sized WC-Co (6-30 wt %Co, or, alternatively, Co/Ni/Cr); courtesy of CERATIZIT S. A.

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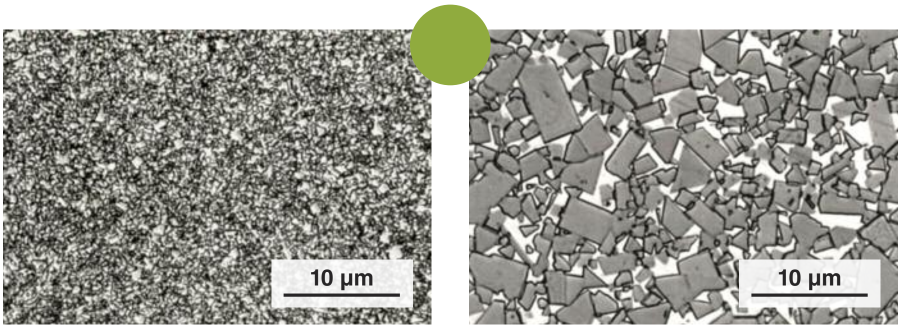
Figure 7: Submicron (left) and extra coarse (right) WC-12 wt% Co grades; the finer the carbide the higher is the hardness, but the lower the toughness, and contrariwise; note that even in the case of the extra-coarse material the size of the WC grains is still in the µm range (1500:1). Typical application ranges: metal cutting, wear parts, wood cutting (left); cold forming tools, recycling, and surface mining (right).



hardness: 1450 HV10;
toughness: 10 MPa√m

hardness: 1070 HV10;
toughness: 20 MPa√m

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From extra coarse to near-nano

The history of cemented carbides is the history of a steadily widening range of available WC grain sizes for processing. The main reason for this widening of the spectrum of WC grades is that besides those variations achieved by the cobalt content, the properties, such as hardness, toughness, strength, wear resistance, modulus of elasticity, etc. can be widely varied by means of the WC grain size. The finer the cemented carbide, the harder is the material, and contrariwise (**Figure 7**).

In industry, the term extra-coarse is used for cemented carbides with mean WC grain sizes of >5 µm (for comparison: the size of typical bacteria is in the range of 1–5 µm), which can still be called fine-grained materials, particularly compared to competitive materials, such as steels or ceramics. Such tools are used in cases where a high abrasion resistance is demanded besides a good impact strength, for example, in surface mining or hot rolling of metals (typically containing 6 to 30% wt% Co or, alterntively Co/Ni/Cr); Figure 6.

In contrast, the term near-nano describes a material with WC grain sizes below 200 nm (0.2 µm). They are used where an extreme wear resistance of the tool is mandatory for an application, for example, water jet nozzles with water pressures up to 4000 bar (tool hardness: HV10: 2800).

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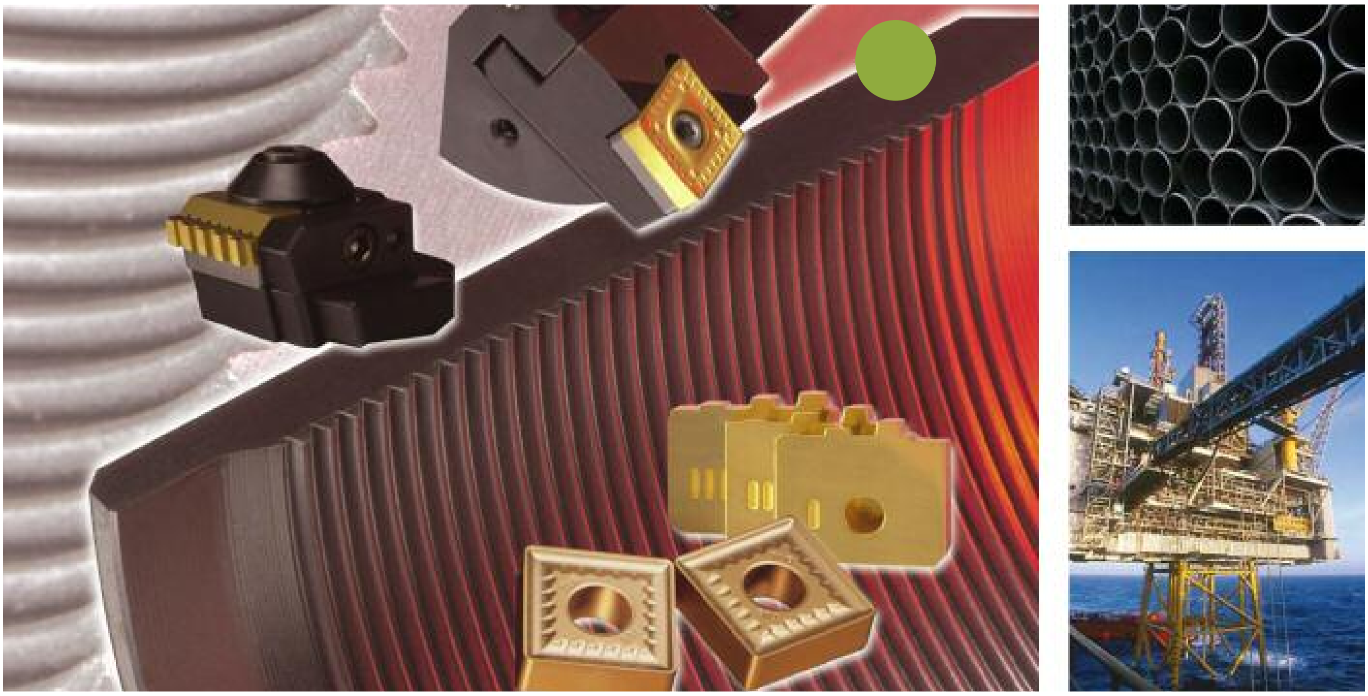

Figure 8: Cemented carbide cutting inserts for threading of tubes; typical grades are coated, fine grained materials (8-12 wt.% Co) with additions of cubic carbides (TiC, TaC); courtesy of CERATIZIT S.A.

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Figure 9: Drilling of printed circuit boards with cemented carbide drills; drill diameters down to 150 µm; rotating speed up to 300,000 rpm; cemented carbides which are used for this application must have a high hardness (ultrafine grain) and high modulus of elasticity (660 GPa) for precision drilling of very small holes into a copper/glass-fiber reinforced plastic laminate; courtesy of AT&S.

Fine grained cemented carbides have been the fastest growing segment of the cemented carbide industry over the last twenty years, due to their high strength (compressive strength up to 8,000 MPa*), hardness and microstructural uniformity at still moderate toughness. They are used for round tools (drills, threaders (**Figure 8**), reamers, routers), tools for the electronic industries (micro tools) (**Figure 9**), as wear parts, chipless forming tools, circular shearing tools, wood machining tools, for can tooling and, more recently, also in the form of a variety of coated and uncoated metal-cutting inserts of complex geometries [3].

Wear parts – the workhorses in the manufacturing industry

The wear parts' segment is probably the most versatile area of cemented carbides, in terms of part size, geometry, and fields of application. It ranges from small balls for ball-point pens, to large rolls used in the hot rolling of steels, or large plungers used in the plastics industry. There is no manufacturing industry, in fact, which does not rely on cemented carbides since wear of materials during mass production is an important operational factor. Generally, WC-Co alloys are used in this specific field. If corrosion occurs as a relevant factor, CoNiCr-, NiCr-, FeNiCo- and pure Ni-binder systems are also taken into consideration.

Cemented carbide wear parts are used in wire and section drawing (**Figure 10**), cold and hot rolling, stone-working, working of wood and plastics, in the textile, magnetic tape and paper industries (**Figure 11**), in the food and medical industries, the glass industry (**Figure 12**), for stamping and punch drawing (e.g. can making) and a large number of structural components, including plungers, boring bars, compacting dies and punches, high pressure dies and punches (**Figure 13**), seal rings, pulverizing hammers, needles, carbide feed rolls, chuck jaws, and others [4,5].

The recycling industry is booming due to the lack of natural resources and, therefore, there is a special focus on recycling of electronic and plastic scrap. In this field, cemented carbides with medium grain sizes (2–3 µm) and binder contents in the range of 9–15 wt% are used which meet the demand for both wear resistance and toughness. Cemented carbide bits are also used for stonecrushing, wood tree stump grinders, mulching or wood shredding (**Figure 14**).

* a strength of 8,000 MPa refers to about 81,5 tons per cm^2; for comparison: a modern high strength concrete exhibits a compressive strength of 100 MPa ~ 1 ton/cm^2 only)

The Viaduc de Millau is the longest cable-stayed bridge in the world (2460 m). About 19,000 tons of steel were used for concrete reinforcement, 5,000 t were used for the cables and stays. Source: http://www.abelard.org/france/viaduct-demillau.php#viaduc).

The wire drawing process is shown below together with the cemented carbide drawing die; drawing dies must have a high abrasion resistance under ambient conditions and at elevated temperatures. Courtesy of voestalpine Austria Draht

Figure 10: Billions of kilometers of steel and copper wire are annually drawn through cemented carbide dies, or, alternatively, hot rolled over cemented carbide rolls; steel wire is used in reinforcement of concrete, for cable cars, in power lines (together with co-drawn aluminium), cable-stayed bridges, suspension bridges but also as steel cord for car tyres, springs, wheel nuts, bearings, screws, etc.; about 100 kg of steel wire are used in a car.

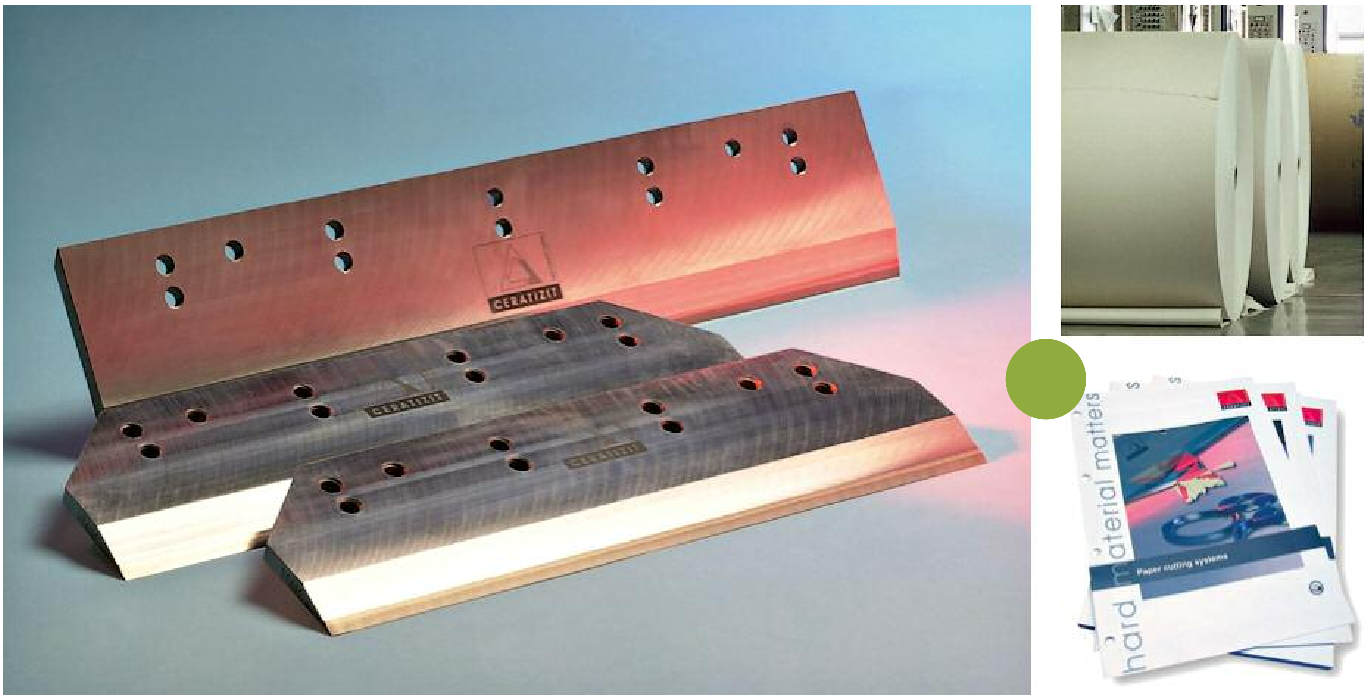


Figure 11: Cutting knifes and slitters for the paper, textile or tape industries made of cemented carbide; typical cemented carbide: submicron to coarse grain sized WC-Co (6 – 12 wt.% Co); abrasion of the tool is increased by hard pigments within the paper, such as rutile titanium white (TiO_2). Courtesy of CERATIZIT S.A.

Figure 12: Glass shearing tools, used for cutting a glass strand into smaller units; this process is highly abrasive; typical cemented carbide: coated, coarse grained WC-Co (8–12 wt.%Co); Cemented carbide tools are also used for the CNC machining of cast iron glass moulds; press-blow plungers for the hollow glass industry are coated with a wear resistant WC-based hardfacings. Courtesy of CERATIZIT S.A.

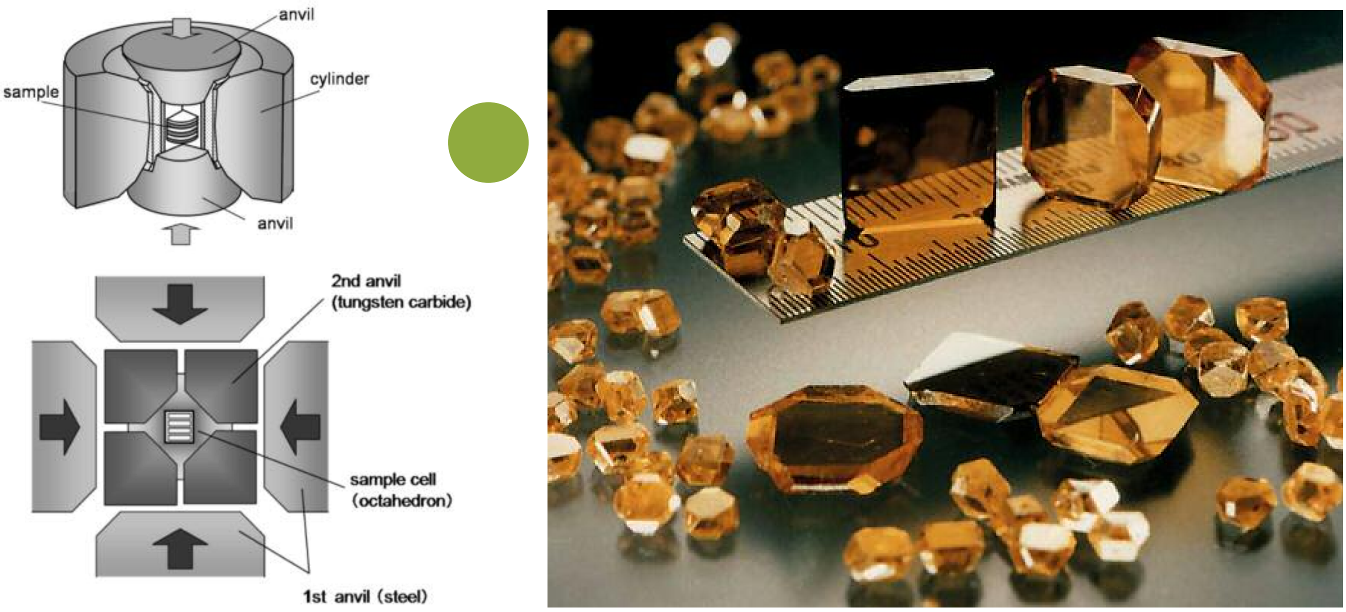


Figure 13: Schematic of a belt and Kawai-type (below) press process used for high pressure diamond synthesis with cemented carbide cylinder and anvils; the cemented carbide has to withstand high process pressures and temperatures (5 to 20 GPa; 1350–1500°C); such presses are also used for PCD and P-cBN parts, pressed and sintered onto a cemented carbide support; synthetic diamond crystals (right); courtesy of Sumitomo Electric. Cemented carbides used in this extreme application must have high compressive strengths (up to 8,000 MPa); grade: fine grained WC and low Co content.

Figure 14: Cemented carbide parts used for wood shredding, but also tree stump grinding, mulching, stone crushing, polymer and textile shredding or chopping of paper roll cores; cemented carbide grades: medium to coarse grained, binder contents between 9–15 wt.%. Courtesy of BETEK.

Machining – a steady source of innovation

In terms of worldwide turnover, this segment is by far the largest. Cemented carbides in this field exhibit WC grain sizes from 0.5 µm to 5 µm and cobalt in the range of 3 to 12 wt%. "Straight grades", which exhibit WC and Co only (despite minor additions of other elements) are used for the machining of cast irons, hardened steel, stainless steels, nonferrous metals (**Figure 15**), nickel-based highstrength alloys, wood, plastics or composites. WC-(W,Ti,Ta,Nb)(C,N)-Co grades (so-called steel cutting grades) are used in machining of steel, especially for long chipping alloys.

Cemented carbide indexable inserts (**Figure 16**) with complex geometries are applied in all kinds of machining operations, such as turning, milling, grooving, threading, drilling, etc. Individual tools are equipped with up to 300 inserts.

Figure 15: Machining of an aluminium wheel rim with a cemented carbide tool; typical cemented carbide: submicron grain size, WC-Co (5 – 8 wt.% Co); the PVD-TiAlNcoated tool with an integrated lubricant layer renders the dry machining of the wheel rim and helps reducing manufacturing cost compared to wet machining. Courtesy of CERATIZIT S.A.

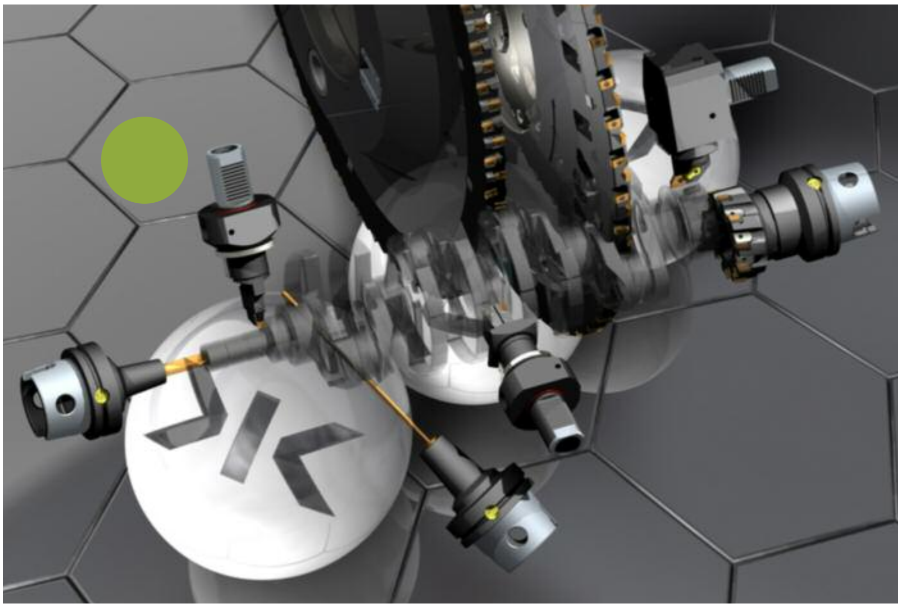


Figure 16: Complete solution of Crankshaft Machining with coated cemented carbide cutting inserts; upper protective coating: TiN (goldcoloured); the image demonstrates the different stages of finishing (drilling, milling,turning); about 8 kg of metal chips are formed on machining. Courtesy of KENNAMETAL INC.

Coatings – an important step further

Coating became one of the most significant developments in the history of cemented carbides, starting in the early 1960s (TiC, TiN) and still progressing today. In coated parts, the carbide plays a different role than in non-coated parts, because it is no longer the active component. The main requirements for protective coatings are high hardness, high wear resistance, low friction values, high thermal stability and high oxidation resistance. The carbide part in turn has to supply the best mechanical support for the coating (rigidity, creep resistance, toughness, thermal properties) and allow perfect bonding to the coating (good adhesion) in order to resist spalling. Coatings are made by CVD (chemical vapour deposition), PVD (physical vapour deposition), medium-temperature CVD and plasma-activated CVD. The latter technique is now successfully used for producing diamond layers onto the cemented carbide substrate. The keenest edges are today produced by PVD coatings. The thickness of the coatings is in the range of 5–20 µm (CVD) and 2–8 µm (PVD).

Today, more than 80% of all turning inserts and about 70% of milling inserts are coated. Also the proportion of PVD-coated drilling tools is steadily increasing. The newest generation are multi-layer coatings with exactly tailored properties for the respective application (material), including true nanocrystalline layer sequences (**Figure 17**). Several hard and superhard coatings are today state-of-the art in the manufacturing industry: TiC, TiN, Ti(C,N), Al_2O_3, TiB_2, TiAlN, AlCrN and several new tailor made quaternary coatings TiAlMeN, AlCrMeN (Me = Si, B, V, Ta, Mo, Nb...), diamond, diamond-like carbon, and most recently also PVD Al_2O_3.

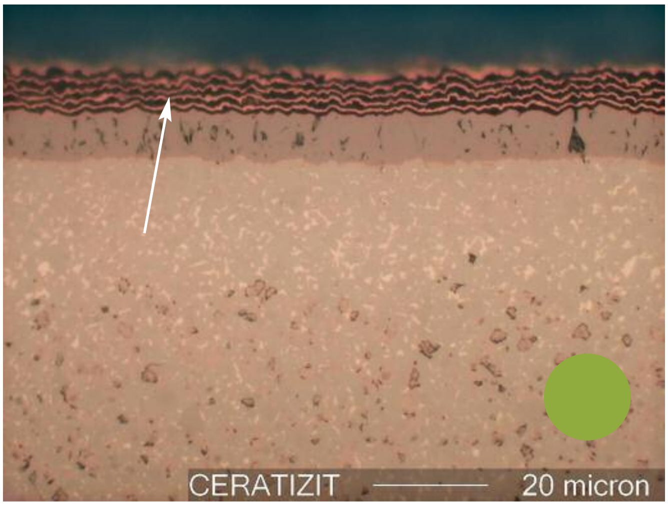


Figure 17: Section through a coated cemented carbide insert, used for turning of steels and alloyed steels. The coating consists of a sequence of different thin layers of Ti(C,N), alumina and TiN; the grade exhibits a graduated structure with a cobalt surface enriched zone which significantly improves toughness and resistance to crack formation during machining. Courtesy of CERATIZIT S.A.

Heavy duty – mining and construction

This important and large segment (in particular in terms of tonnages) includes tools for road planning, soil stabilisation, asphalt reclamation, vertical and horizontal drilling (rock-, oil and gas), tunnel boring, surface mining (**Figure 18**), and others. For these applications, impact resistance, abrasion resistance and high fracture toughness are required. Commonly, such cemented carbide grades exhibit coarse WC grain (up to 20 µm) and 6 to 10 wt% Co. To minimize wear on the steel holder of the cemented carbide part during application, WC-based hardfacings are used for wear protection.

Figure 18: Very coarse-grained cemented carbides (WC grain sizes of up to 20 µm) are used for chisels in surface mining of ores or lignite; such materials have to combine good wear resistance with a high toughness due to impact exposure; compared to steel chisels cemented carbides behave much more wear resistant, and, therefore, significantly improve tool life helping to reduce the cost of maintenance. Courtesy of BETEK.

Cemented carbides – an important partner in compounds

Cemented carbide parts are frequently joined onto other materials, in particular steel. It is of utmost importance that the joining of the material compound can withstand the forces acting during application, and does not form the weak point of the part. In this regard, cemented carbides behave in exemplary fashion and allow all the important joining techniques, such as brazing, laser welding, pressure welding, or projection welding. An example is demonstrated in **Figure 19**.

Even more, cemented carbides are used as a support for polycrystalline diamond or cubic boron nitride cutting tips (**Figure 20**), or as matrix alloy for diamond grit, used in rock drilling and oil mining. This partnership significantly expands the application field of cemented carbides to the range of super hard materials. Modern drill heads consist of a layer of polycrystalline diamond integrally sintered to a tough tungsten carbide substrate under high pressure and high temperature. Such PDC cutters (polycrystalline diamond compact) combine the high hardness and abrasion resistance of diamond with the impact resistance of cemented carbides and provide a faster, more durable and cost-effective drilling.

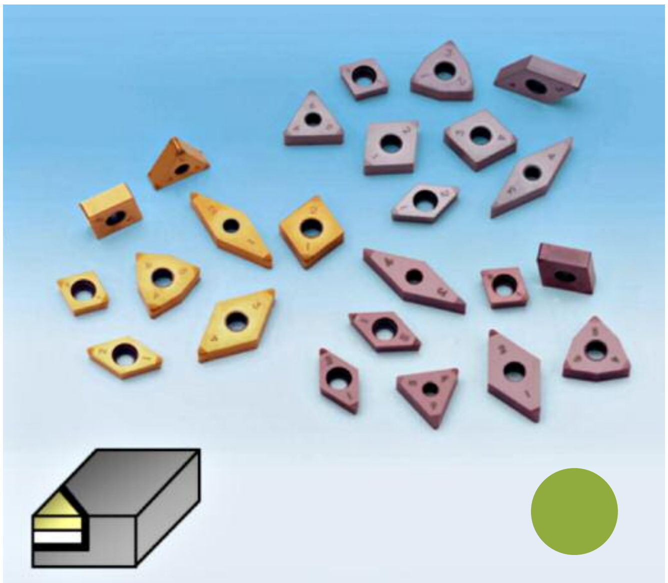
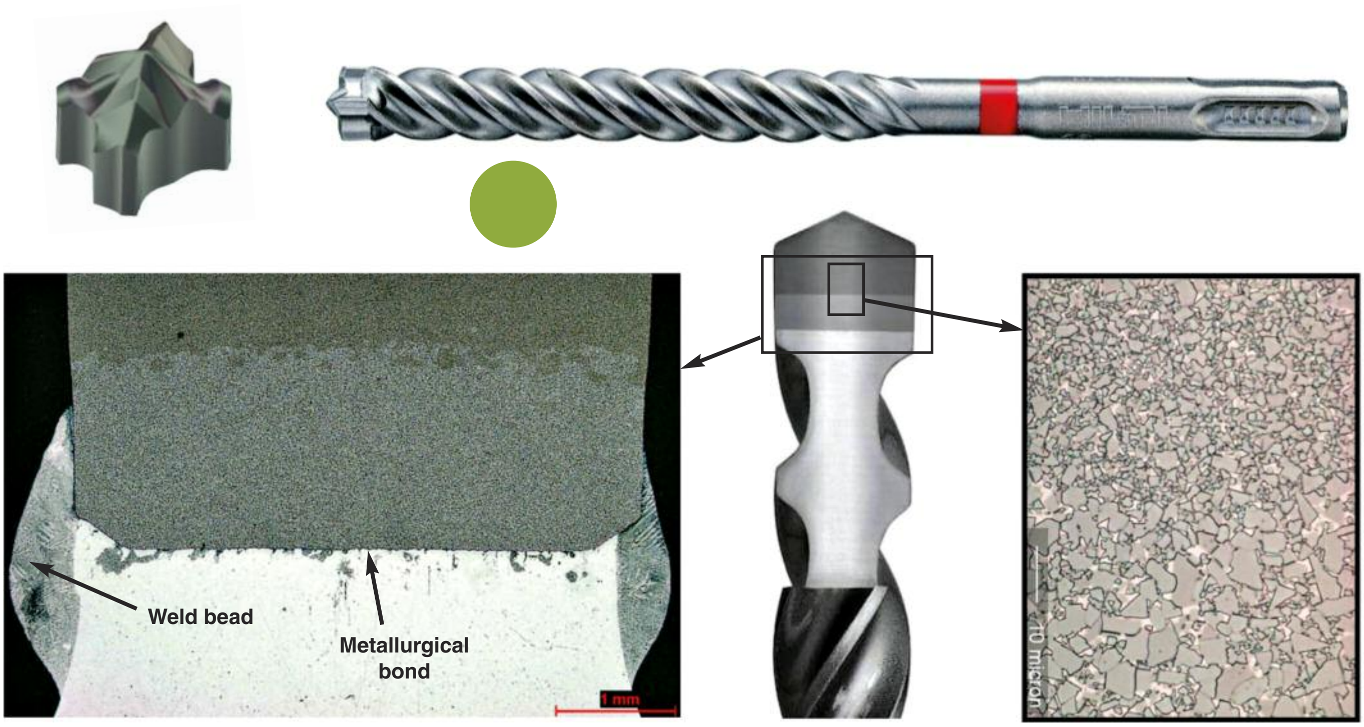


Figure 20: Cemented carbide supported superhard cutting inserts; diamond and cubic boron nitride are sintered onto a cemented carbide support under high pressure and temperature (1350°C; 5.5 GPa); the material compound is subsequently brazed onto a cemented carbide insert. Courtesy of Sumitomo Electric.

Figure 19: Graded head for hammer drills, made by advanced pressing and sintering technology; the graded head consists of a hard and wear resistant upper part, and a lower, much tougher part with significantly coarser microstructure and improved weldability. Courtesy of HILTI AG and CERATIZIT S.A.



“The tooling industry has entered the Tungsten age” [7]

More than 80 years since their introduction as tool material, cemented carbides have gained a strong position in the tooling and construction industry, in particular in automated manufacturing. The main reason for this success has to be seen in the unique combination of high hardness and toughness compared to other hard tool materials, such as ceramics, cermets or diamond.

The introduction of coated cemented carbide grades in particular has strengthened their position as it is now possible to tailor the respective coatings to the respective machining problem (material, machining conditions), which has led to considerable increases in productivity of manufacturing.

Powder metallurgy offers a simple and flexible route of mass production of parts with complex geometries and improved design (including metal injection molding and slip casting), and modern technologies, such as pressure-aided sintering have significantly contributed to the high reliability of the materials during application which is a prerequisite in automated manufacturing. Modern joining techniques and the formation of graduated materials have further broadened the application range of cemented carbide tools and the development of polycrystalline diamond integrally sintered to a tough cemented carbide substrate under high pressure is a good example of a recent innovation.

Cemented carbides remain a growing market. There has been a continuous expansion in the consumption, from an annual world total of 10 tons in 1930 to about 50,000 t in 2008. As the world’s economies grow, cemented carbides will play their part in the progress of technology.

New technologies and new materials will demand new tooling solutions, and cemented carbide tools will provide a cost-effective option due to their attractive properties (**Figure 20**). Modern recycling technologies and a more efficient collection system of scrap material will contribute in this regard, driven by both the price and the need to maintain and save natural resources. In the long term, recycling will inevitably become a key strategic factor for sustained economic growth, and the respective recycling strategies of cemented cabides are on the line.

So, after a period of about 80 years, cemented carbides have developed from a temporary solution in industry (as a substitute for diamond in wire-drawing in the lighting industry) to a very succesful and almost irreplaceable material for the manufacturing industry.

Figure 21: Different stages of manufacturing of a modern airliner; riveting robot for Airbus side shells (left); orbital outline milling robot (top right) and milling of aerostructures at the Augburg plant (bottom right). Courtesy of Premium AEROTEC.
Diamond coated cemented carbide tools are used for the drilling of holes into carbon-fiber-reinforced composites; other grades are used for the drilling, milling and turning of high strength steels, aluminium and titanium alloys; about two million holes have to be drilled into the fuselage for the riveting of the CFC-parts with the metallic spars and stringers.

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[6] www.tribo.de/e1/P1/Plunger_Packing_Lubricant.aspx

[7] The Tungsten Age; expression used by Martin James, formerly with Sandvik Hard Materials, to underline the importance of cemented carbides in modern tooling.

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