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Recent Developments in Hard Cutting Tool Materials

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ABSTRACT

Recent developments in practical hard cutting tool materials are reviewed. The materials reviewed are WC-baced cemented carbides, coated cemented carbides, TiC-based cermets, ceramics, sintered diamonds, sintered CBN, diamond coatings and CBN coatings. Developments and improvements of cutting tool materials are showing remarkable progress in answer to expanding demands in cutting and diversifing work materials. To prolong the tool life in cutting with increasing speed and feed rate, great efforts have been made to improve both the wear resistance and strength simultaneously. Through development of new materials, elimination of defects in the materials, surface modification, etc. successful improvements have been accomplished.

1. INTRODUCTION

At present, a variety of hard cutting tool materials are used depending on the cutting conditions and work materials. They are cemented carbides, coated carbides, cermets, ceramics, sintered diamond, sintered cubic boron nitride (CBN) and so on. Furthermore, each of them is manufactured in different grades to meet the particular applications requirements. These hard cutting tool materials are comparatively new materials and are called new ceramics or fine ceramics. The cemented carbides have been in the market for over 50 years and the others for periods ranging from 5-30 years. The properties and cutting performance of these materials are constantly being improved and new grades are developed one after another. This text mainly describes the progress in the hard tool materials from the viewpoint of industrial applications.

2. TRENDS OF CUTTING AND CUTTING TOOLS

Recent trends of cutting applications and demands for cutting tools and tool materials are shown in Table 1. The overriding consideration is to increase cutting productivity or metal removal rate, by a higher speed and a higher feed rate cutting. This calls for cutting tools with longer life and higher reliability in these severe conditions. The reliability is especially important to promote efficient factory automation. Another trend observed is in the nature of the work materials - larger volumes of difficult-to-cut materials such as super alloys, high silicon aluminum alloys and hardened steels and hard cast irons are required to be handled today.

Cutting	Cutting Tools	Tool Materials
High speed	High wear resistance	Fine and uniform structure
High productivity	High strength	Defectless
Precision machining	High reliability	Less impurities
Diversified works	High accuracy	Surface modification
Factory automation	Diversified shapes	Diversified materials
Chip control	Chip breakers	

Table 1
Recent trends of cutting and demands on cutting tools and tool materials.

Cemented carbides were brazed on steel shanks for use as cutting tools. Change from brazed tools to insert tools, where cutting inserts are mechanically fixed on the tool holders, occurred in the mid-1950s. the majority of the recent cutting tools is of the insert type. The developments of insert tools have made significant contributions not only towards the evolution of tool geometries including those for chip breakers, but also for the development and diversification of the tool materials. Difficult-to-braze tool materials like cermets and ceramics can now be fitted into cutting tools in the form of inserts.

On the side of cutting tool materials, great efforts have been made to improve both the wear resistance (hardness) and strength (toughness) simultaneously. Generally, wear resistance and strength are mutually incompatible properties. It is almost impossible to improve both of them by a single process, for instance, by a simple change of the chemical composition. Various factors such as composition, grains size and its distribution, additives, uniformity in the microstructure, content of nonmetallic elements such as C and N, extent and nature of impurities, defects such as pores, etc., will have to be carefully controlled for this to be accomplished.

These hard tool materials show typical brittle fracture, and the apparent strength, for example TRS (transverse rupture strength), is strongly influenced by the defects where the initial crack is generated. In the case of cemented carbides and cermets, the main defects where the fracture originates are pores, large hard particles and segregated binder metals (lump) /1/. Aggregation of hard particles and segregation of impurities also act as sites for the origin of fracture /I/. These defects are basically common in all the sintered hard materials. Therefore, strength increases without decrease in hardness when the size and number of the defect are reduced. Though the pores are eliminated by HIPPING (hot isostatic pressing), it has no effect on the other defects; sometimes defects like large particle are increased by grain growth during HIPPING. Therefore, a uniform sintered body with less defect is essentially desirable. For this, very careful control should be exercised throughout the processing, from the production of powders to the final stage of sintering.

New tool materials are presently under development to handle the increasing volumes of new work materials and more severe cutting conditions. This has resulted in the diversification of the tool materials as well as future improvement in their properties.

3. APPLICATIONS OF HARD CUTTING TOOL MATERIALS

The hard cutting tool materials widely used in the present industries are WC-based cemented carbides, coated cemented carbides, TiC-TiN-based cermets, Al_2O_3 and Si_3N_4 based ceramics and sintered polycrystalline diamond and cubic boron nitride (CBN) produced by ultrahigh pressure processing. The key technologies for producing these materials involve powder processing, powder metallurgy, ceramics, chemical and physical vapor deposition, ultrahigh pressure, etc.

These materials have to be properly used in cutting applications according to their properties. Some important properties of the tool materials relating to wear in cutting are listed in Table 2. The hardness and the melting point are related to the high temperature hardness. The cutting edge temperature increases as the cutting speed and feed rate increase. Therefore, the abrasion wear depends on the high temperature hardness, that is, the abrasion resistance itself is reduced as the hardness decreases. Moreover, the wear is accelerated by plastic deformation of the cutting edge, caused by the hardness drop. The free energy of formation represents the thermochemical stability at high temperatures. The higher the thermochemical stability, the better the resistance to the thermal wear caused by diffusion and oxidation in high speed cutting. Another important property is the strength or the toughness to withstand the chipping and breaking of the cutting edge, which is especially severe in high feed cutting and interrupted cutting.

The mutual relations of high temperature hardness and toughness in the tool materials are schematically shown in Fig. 1. Generally, a hard one is poor in toughness, and the hardness decreases as the toughness increases, though coated carbides show relatively higher hardness compared to their hot hardness. As a result, the main application ranges of the tool materials can be schematically defined in relation to the cutting speed and the feed rate, as illustrated in Fig. 2.

Required properties	Hardness Rigidity	Chemical stability	Strength Toughness
Related resistance	Abrasion	Diffusion Oxidation	Chipping Breaking
Cutting conditions	All	High speed	High feed Interrupted
WC carbides	B	D	A
Cermets	B	C	C
Ceramics	A	A	E
Coated carbides	A B	A	B

good: A > B > C > D > E :poor

Table 2
Required properties of cutting tool materials.

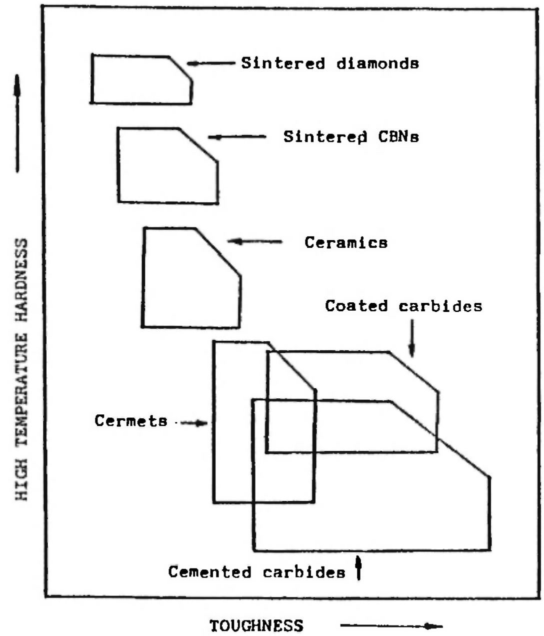


Fig. 1: The relation between high temperature hardness and toughness of cutting tool materials.

Al_2O_3-based ceramics are used in high speed and low feed rate cutting, because they have a higher high-temperature hardness and thermochemical stability but poor toughness. Si_3N_4-based ceramics have greater toughness and can withstand a higher feed rate than Al_2O_3 but their application is limited to gray cast irons because of rapid wear in cutting steels and ductile cast irons. Cermets can be used at a faster feed rate than ceramics and a higher speed than WC-based carbides. However, their applications are still limited in light to medium cutting for want of adequate toughness. WC-based carbides are the strongest among the hard tool materials and they can be used in high feed rate cutting and severe interrupted cutting. But they cannot be used at high speed because of poor thermochemical stability. Coated carbides are composed of a strong carbide substrate and a thermochemically stable hard ceramic surface layer. As a result, they are the best materials for high speed, high feed rate, high metal removal rate, and for cutting. Diamond and CBN have exceptionally high hardness and superior wear resistance, but their present applications are limited to special cases because of tool cost, poor shape flexibility, reaction with some work materials and so on. The main applications of diamond are cutting nonferrous alloys, ceramics and nonmetals, while CBN is ideally

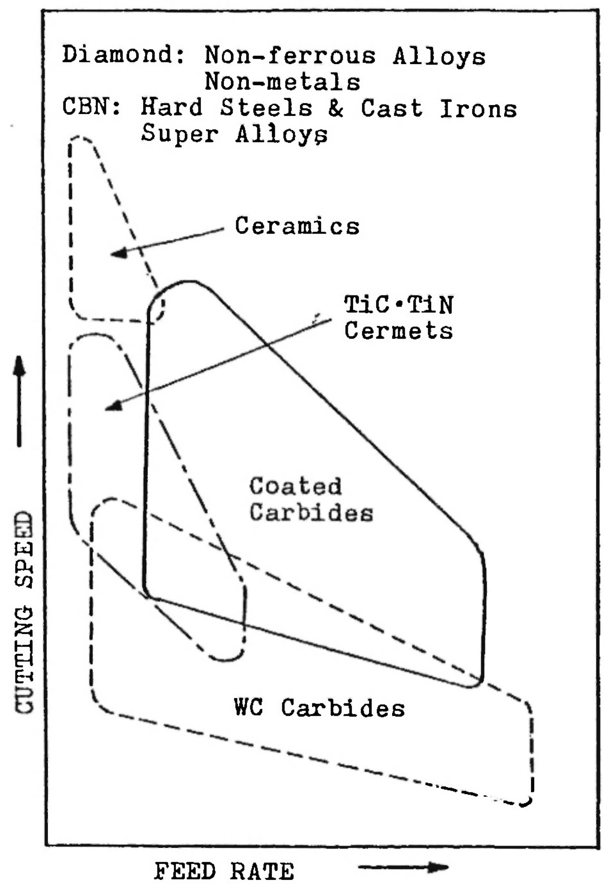


Fig. 2: The main application range of cutting tool materials.

used in cutting super alloys, hardened steels and hard cast irons.

4. WC-BASED CEMENTED CARBIDES

WC-based cemented carbides are the oldest among hard cutting tool materials. The first WC-Co sintered alloy industrially used in cutting tools was developed in the late 1920s. The first stage improvements were made mainly by addition of TiC and TaC. They form complex carbides like (W,Ti)C and (W,Ti,Ta)C which are more stable and less reactive with steels compared with WC. The wear resistance of cemented carbides in steel cutting and high speed cutting is improved by these complex carbides, although the strength is decreased to some extent.

The present standard WC carbides for cutting applications are classified into 3 codes - P, M and K, with sub-classifications like P10, P20 and so on - by the ISO (International Standard Organization) according to the application. The P group is for cutting materials with long chips such as carbon steels, alloy steels and ferritic stainless steels. The cutting is generally accompanied by large cutting force and severe crater wear. The M group is used for cutting materials with long to medium chips such as steel castings, austenitic stainless steels and ductile cast irons. The cutting force is large to medium and chipping is likely to generate at the cutting edge. The group K is for cutting materials other than steels such as gray cast irons, nonferrous alloys and nonmetals. Generally, the cutting force is comparatively small and the wear is mainly abrasion wear.

Examples of chemical compositions and properties of practical WC-based cemented carbides for cutting use are listed in Table 3. Fig. 3 shows a typical microstructure of cemented carbides. The amount of (W,Ti,Ta)C is increased in the structure with increasing TiC and TaC content as shown in Figs. 3b and 3c. The P group carbides contain a large amount of TiC and TaC which increases crater wear resistance. The content of additive carbides is

ISO code	Symbol (Tungaloy)	Composition, wt% WC	TiC	TaC*1	Co	Mean grain size μm	Density g/cm³	Hardness HRA	Transvers rupture strength MPa	Compressive strength MPa	Modulus of rigidity GPa
P10	TX10S	60	18	14	8	1-2	10.6	92.0	1,900	4,600	530
P20	TX20	72	10	10	8	1-2	12.2	91.5	2,000	4,800	540
	TX25	72	8	12	8	1-2	12.3	91.0	2,200	4,800	550
	UX25	69	9	13.5	8.5	1-4	12.3	91.0	2,300	5,000	570
	UX30	72	8	12	8	2-4	12.6	91.0	2,300	5,000	570
P30	TX30	71	8	12	9	2-4	12.6	90.5	2,300	5,000	560
P40	TX40	79	6	4	11	2-4	12.8	89.5	2,300	4,700	510
M10	TU10	75	6	13	6	1-2	13.0	92.5	2,000	5,000	580
M20	TU20	80	4	8	8	1-2	13.4	91.5	2,300	4,900	570
	UX25	69	9	13.5	8.5	1-4	12.3	91.0	2,300	5,000	570
M30	UX30	71	8	12	9	2-4	12.6	91.0	2,300	5,000	570
M40	TU40	72	5	5	18	1-2	13.3	89.0	2,800	4,400	540
K01	TH03	89*2	4	2	5	< 1	13.3	93.5	1,900	6,300	630
K10	TH10	92	-	2	6	1-2	14.7	92.0	2,400	6,200	635
K20	G 2	94.5	-	-	5.5	2-3	15.0	90.5	2,800	5,300	620
K30	G 3	93	-	-	7	2-3	14.8	90.0	3,200	4,900	580

*1 - includes NbC, *2 - includes 0.5% other carbide

Table 3
Typical practical cutting grades of WC-based cemented carbides.

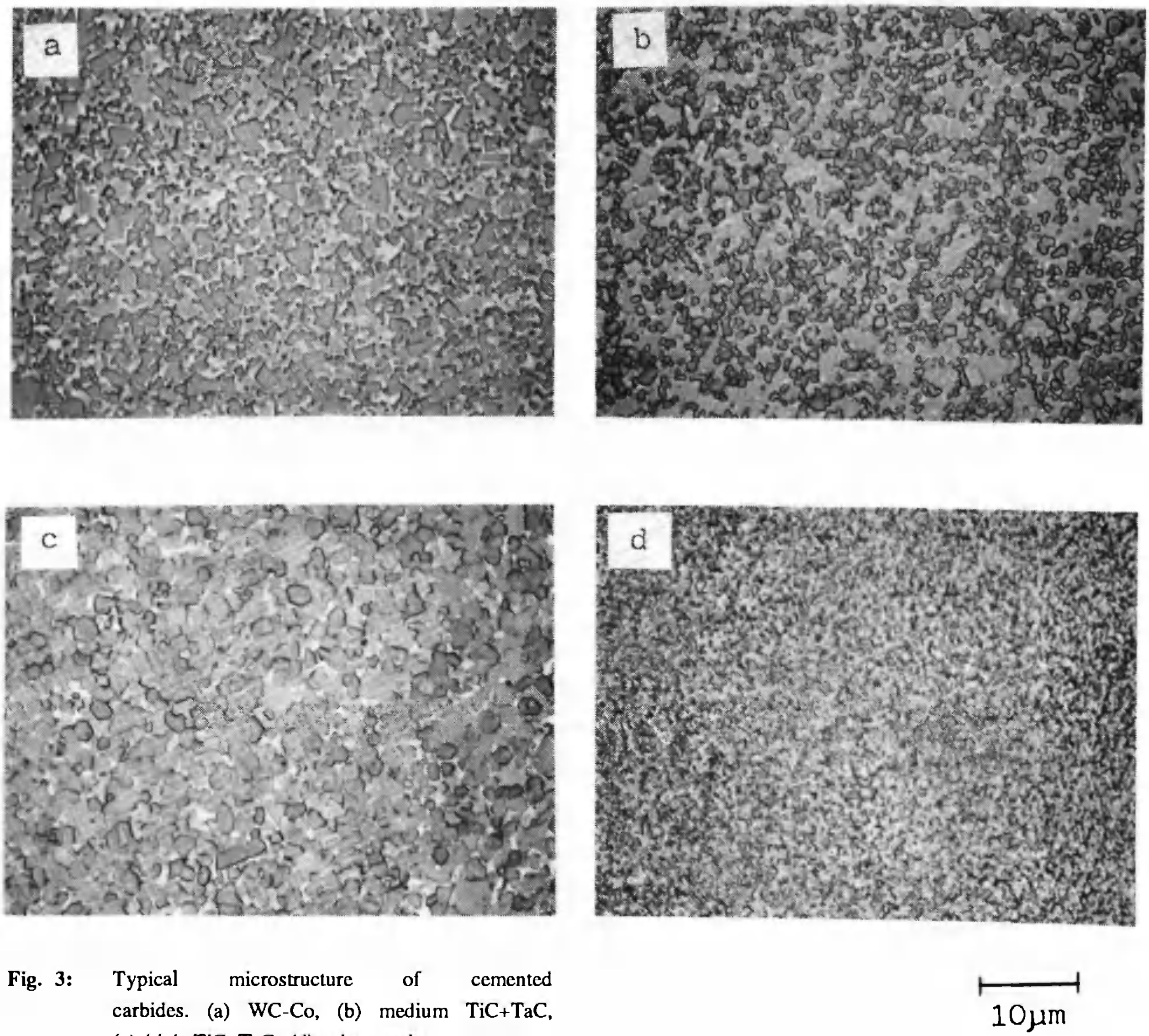


Fig. 3: Typical microstructure of cemented carbides. (a) WC-Co, (b) medium TiC+TaC, (c) high TiC+TaC, (d) micro-grain.

medium in the group M carbides and the K group carbides are basically composed of WC-Co though some of them contain a small percentage TaC as grain growth inhibiter. The grades with a lower class number have a higher hardness, higher TiC-TaC content, a lower TRS and low Co content. The hardness and the TiC-TaC content decrease and the Co content and the TRS increase as the class number increases. Examples of wear and chipping resistance are shown in Fig. 4. The small number grades are used in light to finish cutting. The speed is high but the feed rate is slow and the depth of cut is small, because they have high wear resistance but inferior chipping resistance. The higher number grades are used in medium to heavy cutting, or rough cutting. They cannot be used at high speeds because of low hardness, but a faster feed rate and deeper depth of cut are possible owing to high toughness. They are also used in interrupted cutting, milling and drilling.

The next step was the development of micro-grain cemented carbides in the late 1960s. They consist of very fine and uniform carbide grains as shown in Fig. 3d. The mean carbide grains size of the initial grades was below 1μm compared with 2 to 3μm in conventional cutting grades. The latest grades have a finer grains size of less than 0.5μm. The advantage of micro-grain carbides is their increase

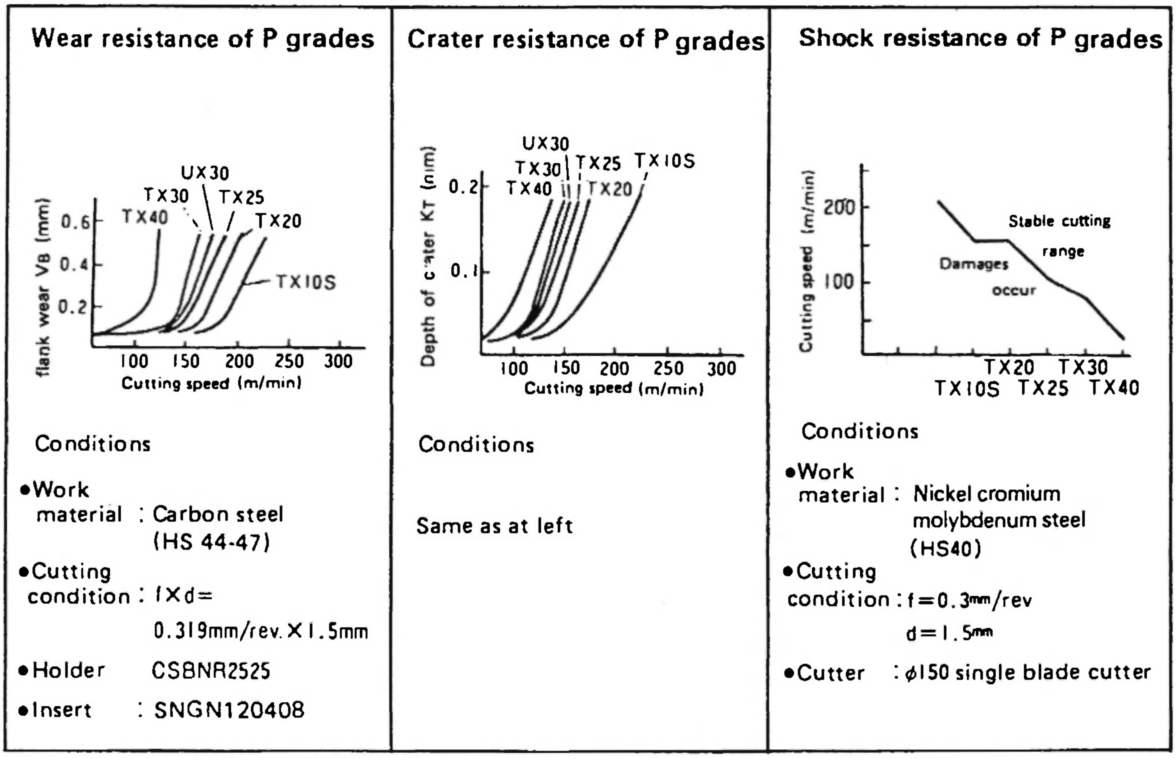


Fig. 4: Example of the tool wear and the chipping of cemented carbides.

in strength without reduction in hardness. Examples of the present micro-grain grades are shown in Table 4. When hardness is the same, the micro-grain carbides show a higher TRS compared to the conventional alloys shown in Table 3. Micro-grain carbides show superior wear and chipping resistance at cutting speeds of 50m/min or lower vis-a-vis high speed steel (HSS) which was the only practical tool material in the past. Though they are used as insert tools, the main applications are solid drills and solid endmills, and they show a higher metal removal rate and longer tool life than HSS.

One of the major achievements in the history of cemented carbides is the accomplishment of control of carbon content. The stoichiometric carbon content of WC is 6.12 wt.%. Cemented carbides, for example WC-Co, show a normal structure consisting of WC and γ-phase (Co) when the carbon content is close to the above value. Free carbon and an η-phase like W_3Co_3C appear in the microstructure when the carbon content is higher and lower, respectively, and the strength decreases in both cases. Therefore, the carbon content had been controlled within the normal structure until the 1960s. The range is about 0.1% /2/ in relation to the carbon content of tungsten carbide. Suzuki et al /3/ discovered in the mid 1960s that the properties of cemented carbides like hardness and TRS are largely altered by the carbon content even within the normal structure range. The carbon content has thus been controlled more severely. The carbon content in the present practical alloys is controlled within the range of 0.02 to 0.03%. The objective of carbon control is the same in the case of cermets.

The recent improvements have been brought about through integration of various means as described in Section 2, though the nominal compositions are not largely different. The main target is to increase the strength, the chipping resistance and the tool reliability without decreasing the hardness and the wear resistance. A typical result can be seen in the relation between hardness and TRS. A new fine grain defectless carbide with a uniform structure, a hardness of RA91 and a TRS of 5.0 GPa /4/ has been developed. The TRS in conventional carbides with the same hardness is 1.8 GPa. As a result, a micro-drill with a cutting edge diameter of less than 0.1 mm has been practically realized.

Table 4
Typical practical cutting grades
of WC-based micro-grain cemented carbides.

Tungaloy symbol	Density g/cm^3	Hardness HRA	Transverse rupture strength MPa	Main cutting applications
F	14.9	93.5	2,500	Single point tools for automatic lathe
M	14.5	92.0	2,700	Brazed tools
EM	14.1	91.5	2,900	Maily for small type solid endmills
UM	13.9	90.5	3,300	Solid endmills, high spiral endmills
H	12.3	90.0	3,300	Cutting tools for shapers, planers

5. COATED CARBIDES

The cross section of some coated cemented carbides are shown in Fig. 5. These consist of several μm thick coating layer and the carbide substrate. The first coated carbide cutting inserts (TiC coated) were marketed at the end of the 1960s. TiN and TiCN coatings were developed soon after and Al_2O_3 coatings entered the market in the mid 1970s. The coatings are formed by CVD (chemical vapor deposition). These coatings are used both as a single-layer and as a multi-layer, but Al_2O_3 coatings require, in principle, and intermediate layer such as TiC to increase the adhesion strength. PVD (physical vapor deposition) coatings were introduced in the early 1980s. The most popular PVD coatings are TiN single layer coatings obtained by reactive ion plating. Other methods, like arc discharge plating and sputtering, are also in practical use.

The resistance, especially thermal wear resistance, of cemented carbides is remarkably improved and the tool life is prolonged several times by coating with hard ceramics such as TiC, TiN and Al_2O_3. Coated carbides basically have both the advantages - the wear resistance of ceramics and the strength of cemented carbide. They give superior cutting performance in high speed and high feed rate cutting, compared to cemented carbides which rapidly wear, and cermets and ceramics which cannot withstand the conditions because of chipping. As a result, they command the biggest market in cutting inserts.

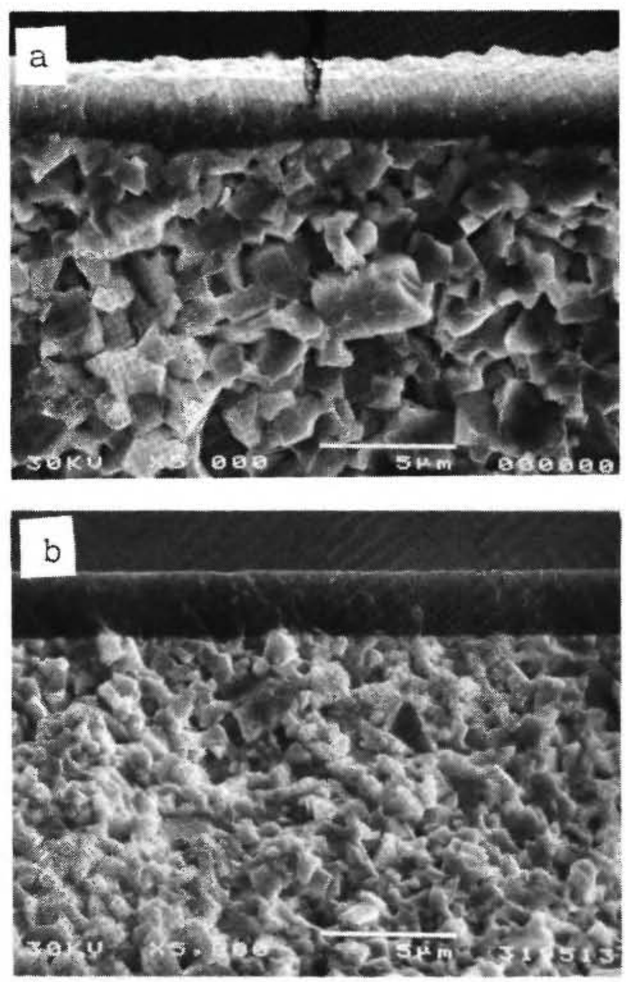


Fig. 5: Typical microstructure of coating layers. (a) CVD TiC-Al_2O_3, (b) PVD TiN.

The main factors influencing the cutting performance of coated carbides are the kind of coatings, the thickness of coating layer, the coating method and the substrate. The wear characteristics of coatings depend on the kind of ceramics. Properties of ceramics used for the coatings are listed in Table 5. The abrasion wear of coatings is related to the hardness and the thermal wear depends on the thermochemical stability represented by the free energy of formation. A V-T diagram showing the relation between the tool life (T) and the cutting speed (V) is given in Fig. 6 /5/. An Al_2O_3 layer, with its superior thermo-chemical stability, shows a longer tool life than

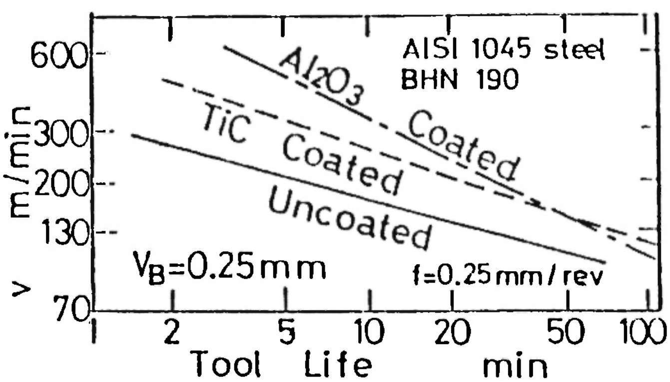


Fig. 6: The tool life of coated carbides.

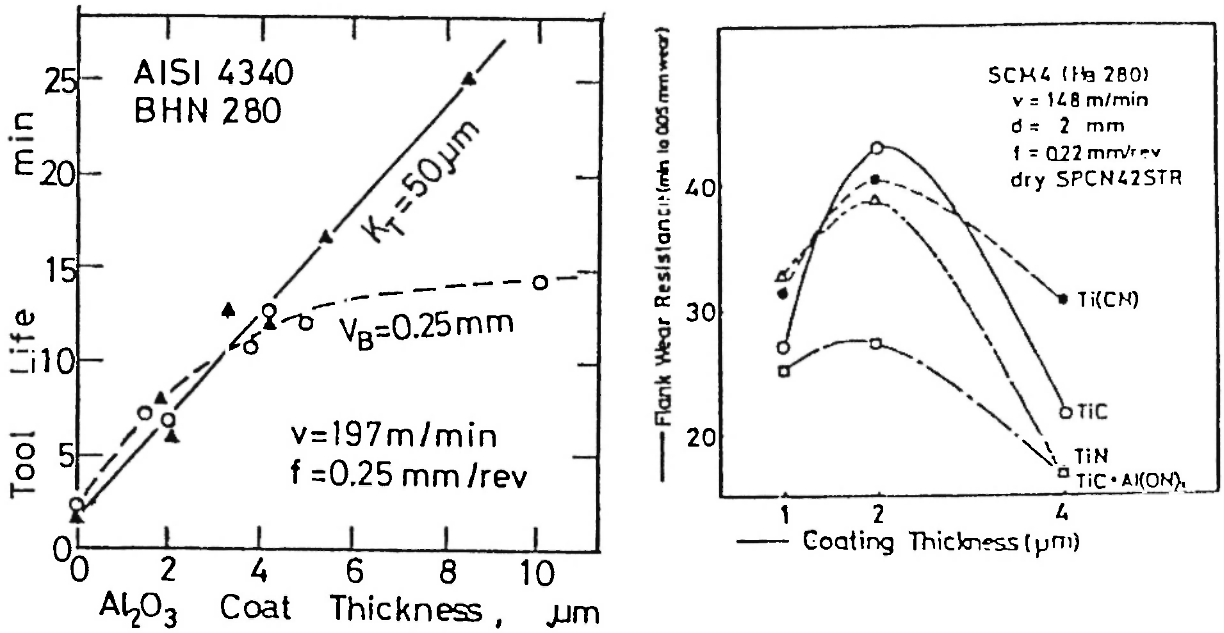
TiC at high cutting speeds, where thermal wear is dominant. The tool life increases as the cutting speed decreases and a TiC layer with higher hardness gives longer tool life than Al_2O_3 at low speeds where wear is mainly caused by mechanical abrasion The general order in thermal wear resistance is Al_2O_3>TiN>TiCN> TiC and that in abrasion wear is the contrary. Therefore, Al_2O_3 coatings are used in high speed cutting, while TiC is suitable for low speed cutting in the speed range employed for coated carbides.

The effect of coating layer thickness on the tool life is shown in Fig. 7. In turning, though the life based on crater formation increases with thickness, that based on flank wear is almost saturated above 5 μm (Fig. 7a) /5/. Moreover, flaking-off is likely to occur in a too-thick coatings. Therefore, the thickness is generally controlled at 5 to 10 μm in practical tools. In milling, micro-chippings occur in the thick layer by repeated shock on the cutting edge and, consequently, the longest life is obtained at about 2 μm (Fig. 7b) /6/. The effect of the kind of coating layers are also compared in Fig. 5b. The tool life of an Al_2O_3 coated insert is shorter than that of TiC and TiN coated ones because micro-chipping is likely to occur in the Al_2O_3 layer since it is weak in both mechanical and thermal shocks.

Table 5
Properties of hard ceramics used for coating layers.

Material	Density g/cm^3	Melting point °C	Hardness Hv	Free enrgy formation $-\Delta F°_{298}$, kj/mol	Coefficient of thermal expansion 10^{-6}/K	Thermal conductivity W/mk
TiC	4.94	3,150	3,000	236	7.7	29
TiN	5.44	2,950	2,100	308	9.4	19
Al_2O_3	3.98	2,300	2,300	1,582	8.0	30
Diamond	3.58	3,700*1	10,000	3	3.1	2,000
CBN	3.48	2,970*2	4,700	114*2	4.7	1,300
Cemented carbides	11-15	1,298*3	1,300-1,800	(38)*4	5-6	30-80

*1 - graphite, *2 - hexagonal BN, *3 - eutectic point of WC-Co, *4 - WC



(a) Turning (b) Milling

Fig. 7: Effects of coating thickness on the tool life of coated carbides. (a) turning, (b) milling.

Fig. 8 shows the change in the TRS of coated carbides with coating thickness /7/. The TRS of CVD coated carbide decreases as the thickness increases, while it does not change for the PVD coated carbide. CVD is carried out at about 1000°C and the brittle decarburized phase (η-phase) as shown in Fig. 9 is likely to form near the surface of the substrate. Furthermore, cracks caused by the difference in the coefficient of thermal expansion, are often generated in the coating layer. PVD coatings are free from these defects as they are treated at a low temperature of about 500°C. In addition, the residual stress in a CVD coated layer is tensile, while that in a PVD one is compressive. Hence the PVD coated carbide has a higher TRS, and consequently, a higher chipping resistance than the CVD one. However, the adhesion strength and the wear resistance are superior in CVD coatings. Owing to this difference in their properties, CVD coatings are used in general turning and milling, while PVD coatings are employed where the tool life of CVD is short due to chipping caused by a high cutting force like in milling stainless steels. PVD is also applied to tools with sharp cutting edges such as solid drills and endmills.

The cutting performance of coated carbides is strongly influenced by the properties of the substrate as the coating layer is very thin. The flank wear of cutting tools is accelerated by plastic deformation of the cutting edge. Therefore, even in the same coating layer, the flank wear decreases as the hardness of the substrate increases because the deformation at the cutting edge is small. On the other hand, the chipping resistance of

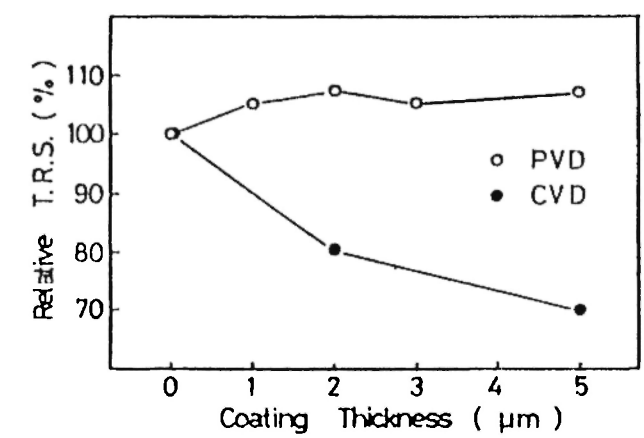


Fig. 8: The transverse rupture strength of coated carbides.

coated carbides rises with increase in the toughness of the substrate. When the cutting edge is free from chipping as in light cutting, coatings on a hard substrate show a longer tool life. In heavy cutting and severe interrupted cutting, elimination of chipping by a high toughness substrate results in a longer tool life, even though the normal wear is greater than in a hard one.

Recently, a complex substrate with a special tough layer near the surface is often used in heavy cutting to improve chipping resistance. One of the methods is enrichment of Co content near the surface by slow cooling a high carbon alloy from the sintering temperature in a weak decarburizing atmosphere /8/. The surface layer has lower hardness and higher toughness compared to the interior. Another tough surface layer produced by reducing (W,Ti,Ta)C in the layer is in practical use too. The layer is formed by sintering a nitrogen containing WC-TiC-TaC-Co alloy in a denitriding or decarburizing atmosphere /9/. Thickness of these tough layers in a practical substrate is generally of the order of several tens µm. Crack propagation from the coating layer into the substrate is prevented or delayed by these tough layers and consequently the chipping resistance is increased. Though the wear resistance is somewhat decreased, the extent is far smaller compared with that in the case of monolithic low hardness tough substrates.

Initially, a few coated grades were enough to compete with the other tool materials. However, to

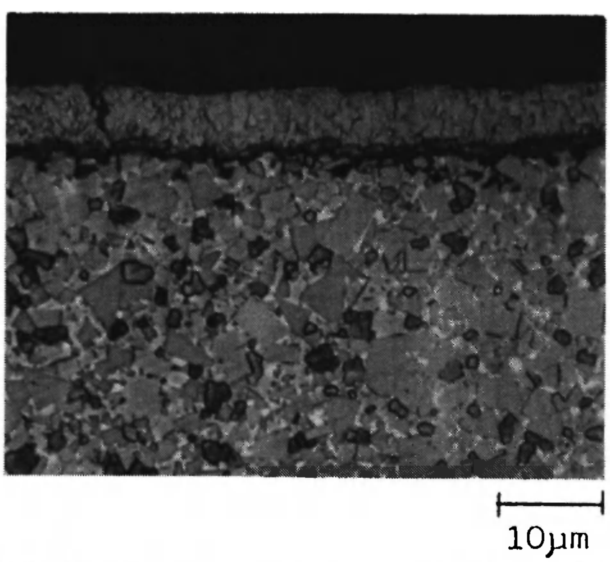


Fig. 9: The decarburized phase and crack generated in CVD coatings.

satisfy increasing demands in a variety of cutting applications, several new grades of coated carbides are being developed and perfected year by year. Table 6 shows examples of the present standard coated carbide grades. They are different from each other in the kind of coating, combination of coating layers, layer thickness, coating method, substrate, etc. Proper combination of these factors is indispensable to fabricate satisfactory coated tools for each application and cutting condition.

6. TIC-BASED CERMETS

Examples of the present practical TiC-based cermets for cutting tools are listed in Table 7. Cermets have a unique history of progress amongst tool materials. Although the first generation of practical cermets were developed in the USA in the mid 1950s /10/, they did not attract much attention in the USA and Europe because of insufficient toughness. However, they were highly appreciated in Japan as a less expensive material with less resource problems since they did not contain W and Co. The improvements up to now have been accomplished mainly in Japan, and they became popular and were in use mainly in Japan for many years. This success story of cermets in Japan aroused renewed interest in them in the USA and Europe after the mid 1980s, and thereafter rapid growth in the use of cermets has taken place in these countries too.

A TiC-Mo-Ni alloy, the prototype of the present cermets with the microstructure as shown in Fig. 10a, was developed in the mid 1950s and marketed in the early 1960s. Nickel has good wettability to TiC and addition of Mo improves the strength of TiC-Ni alloys. Later, Mo was replaced by Mo_2C which helped in decreasing the thickness of the intermediate layer formed around TiC and thereby increased the strength. The cermet offers the advantage of higher cutting speed compared to WC-based carbides, as TiC is thermochemically more stable than WC. But the applications of the first generation cermets, TiC-Mo-Ni and TiC-Mo_2C-Ni, were limited to areas in light cutting because their toughness and chipping resistance were poorer compared with WC-based cemented carbides. These alloys have been superceded and are no longer used in practical cutting tools.

Attention was paid to improve the strength and chipping resistance of cermets. They were improved

Table 6
Typical practical cutting grades
of coated carbides.

Tungaloy symbol	Substrate	Coating layer			Main applications Cutting corresponding ISO codes
		CVD/PVD	Type *	Thikness	
T221	K10	PVD	TiN	~ 2 μm	turning K01-K20
T260	P30	PVD	TiN	2	milling P20 P30, M20 M10
T370	P30	CVD	TiC	2	milling P20-P30, M20-M30, K01-K30
T530	K20	CVD	TiC+TiCN+TiN	6	turning K10-K20
T553	P30	CVD	TiC	6	turning P10-P30
T801	M10	CVD	$TiC+Al_2O_3$	7	turning K01-K10
T802	P25	CVD	$TiC+Al_2O_3$	7	turning P10-P20, M10-M20, K01-K20
T803	P30	CVD	$TiC+Al_2O_3$	7	turning P10-P30, M10-M30, K10-K20
T821	M10	CVD	$TiCN+Al_2O_3+TiN$	7	turning K01-K10
T822	P25	CVD	$TiC+NAl_2O_3+TiN$	7	turning P01-P20, M10
T823	P30	CVD	$TiCN+Al_2O_3+TiN$	7	turning P10-P30, M10-M30, K10-K20
T313V	P25	CVD	$TiCN+Al_2O_3+TiN$	2	turning special for threading

* The layers are mostly composed of complex compounds like Ti(ONO), Al(ON)x, etc.

Table 7
Typical practical cutting grades
of TiC-based cermets.

Tungaloy system	Base system (hard phase)	Density g/cm³	Hardness HRA	Trans. rupture strength, MPa	Main applications
X407	TiC-TaC	6.5	91.5	1,600	steel, light to medium turning, light milling
N302	TiC-TiN-TaC-WC	6.4	93.5	1,400	ductile cast iron and hardened steel, light to finish turning
N308	TiC-TiN-TaC-WC	7.0	92.0	1,700	steel, general turning and milling
N350	TiC-TiN-TaC-WC	7.0	92.0	1,800	steel, medium turning
NS540	TiC-TiN-TaC-WC	7.0	91.6	2,000	steel and nonferrous alloys, medium to heavy milling

by additions of TaC and WC in the beginning of 1970s. As a result, the applications were expanded to include turning with a medium feed rate and light milling. This provided the turning point in the use of cermets and the main application of these second generation cermets was directed towards low speed - higher feed rate cutting rather than the higher speed cutting expected in the beginning. An example of their microstructure is shown in Fig. 10b. They are not the main cermet now but are still used in some applications, especially in finishing.

The third generation cermets are based on TiC-TiN (Fig. 10c). A part of TiC was replaced by TiN {or Ti(C,N)} in the mid 1970s. The grain size of the hard phase in the sintered alloy becomes finer and the hardness is increased by addition of TiN. However, residual pores are likely to increase and cause reduction in the apparent strength, like TRS, because of decrease in wettability. Nevertheless, the intrinsic strength, the strength of the defectless alloy, increases with the addition of TiN up to 15% TiN /11/. Thus, with the elimination of pores through process control, it is now possible to use TiC-TiN-based cermets for practical cutting tools. They have a higher wear resistance and chipping resistance compared to the previous types. As a result, most of the present practical cermets are TiC·TiN alloys. Initially, TiN content was less than 10% but, with progress in production technologies, the highest TiN content now exceeds 25%. The present widespread utilization of cermet tools has come about because of the development of these TiC-TiN alloys.

7. CERAMICS

Examples of ceramics presently in use for cutting are listed in Table 8. The first sintered Al_2O_3 ceramics, as shown in Fig. 11a, were first used for cutting in the late 1950s. They are composed of Al_2O_3 and a small, usually about 1%, quantity of sintering aids such as MgO. The TRS and K_{IC} (fracture toughness) of sintered Al_2O_3 are 400-500MPa and 3-4MN/m$^{3/2}$, respectively. Al_2O_3 has the highest thermochemical stability among tool materials and shows the best wear resistance in high speed cutting. On the other hand, application is limited to certain specific tasks in light turning because of poor chipping resistance. It is still in practical use, though the volume is very small.

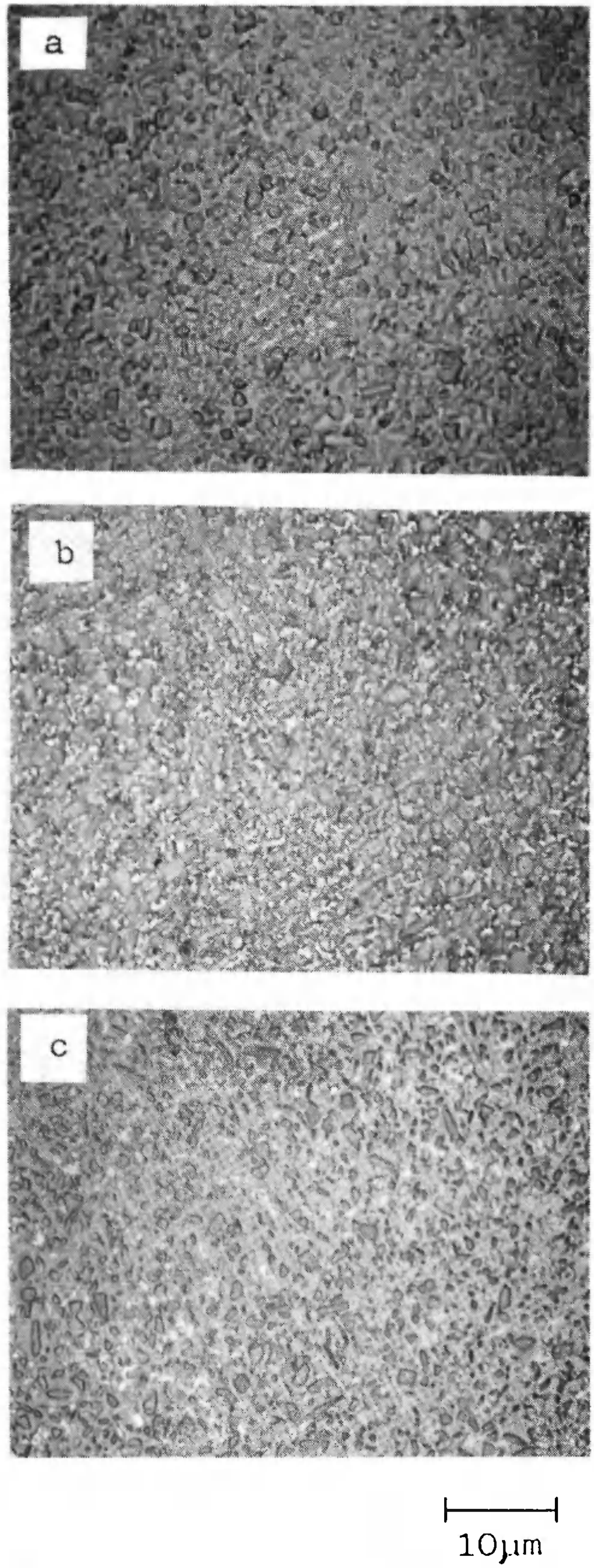


Fig. 10: Typical microstructure of cermets. (a) TiC-Mo_2C-Ni, (b) TaC and WC added, (c) TiN added.

Table 8
Typical practical cutting grades of ceramics.

Tungaloy symbol	Base system	Density g/cm^3	Hardness 25°C HRA	Hardness 1000°C Hv	Transverse rupt. str. MPa	Fracture toughness MN/m$^{3/2}$	Main applications
LXA	Al_2O_3	3.98	93.9	710	50	3.3	cast iron, finish turning
LX10	Al_2O_3-TiCN	4.30	94.0	670	90	5.7	turning hardened steel
LX21	Al_2O_3-TiC	4.24	94.3	770	80	4.3	cast iron, general turning
FX920	Si_3N_4	3.27	92.6	1,100	100	9.4	gray cast iron, rough to medium turning and milling, dry and wet

Hot-pressed Al_2O_3-TiC ceramics were developed in the early 1970s and these were employed to improve the chipping resistance and reliability of ceramic cutting tools. A typical microstructure is shown in Fig. 11b. The TRS and K_{IC} are increased to 800-1000MPa and 4-5MN/m$^{3/2}$ respectively and, consequently, the chipping resistance is fairly improved. They are the main cutting ceramics at present and are mainly responsible for the entry of ceramic cutting tools into the market. The sintering process is gradually changing from hot-pressing to HIPPING to reduce production cost and increase productivity. The strength and chipping resistance of sintered/HIPPED ceramics were inferior to those of hot-pressed ones in the early years but they have been improved to the same level now. Other composite ceramics such as Al_2O_3-ZrO_2, Al_2O_3-TiCN, etc. are also now available. The former are mainly used in cast iron cutting. Some of the latter show superior performance in cutting hardened steels and hard cast irons and compete well with sintered CBN in cutting costs /10/.

Hot-pressed composite Al_2O_3 ceramics reinforced with 20 to 30 vol% SiC whiskers were developed in the mid 1980s /13, 14/. Though their TRS is nearly the same as that for Al_2O_3-TiC, their K_{IC} is much higher, around 9MN/m$^{3/2}$. As a cutting tool, the flank wear of an Al_2O_3-SiC(W) ceramic is somewhat inferior to an Al_2O_3-TiC one, as SiC tends to react with ferrous alloys at high temperature. On the other hand, the chipping resistance and the edge notching are remarkably improved by the SiC whiskers owing to mechanical reinforcement by the whiskers and to the higher oxidation resistance of SiC compared to that of TiC. As a result, they give superior cutting performance in the case of super alloys where the major damage to ceramics occurs in the form of chipping and breakage caused by edge notching.

Si_3N_4-based ceramics (Fig. 11c), typically Si_3N_4-Al_2O_3-Y_2O_3, sometimes called Sialon, have been used in cutting tools since the early 1980s. The biggest advantage of Si_3N_4-based ceramics is their toughness with K_{IC} values of 6-9MN/m$^{3/2}$. The feed rate can therefore be doubled compared to the conventional Al_2O_3-based ceramics. However, their wear resistance is comparatively low, being very rapid in cutting steels and ductile cast irons. Attempts have been made to coat Si_3N_4 with Al_2O_3, TiN, etc. to improve the wear resistance but, so far, the results have not been very encouraging. The present applications of Si_3M_4 ceramics are limited to turning and milling of gray cast irons and, sometimes, to turning of super alloys.

8. SINTERED DIAMONDS

Single crystals of natural diamond have been used as cutting tools for more than 200 years. At present, however, their applications are limited to super precision turning, and most of the cutting tools are made of sintered polycrystalline diamonds produced by ultrahigh pressure technology. Sintered diamond was developed in the early 1970s /15/. It is composed of diamond particles and a small amount of binder metals like Co, illustrated by Fig. 12. The practical sintered diamond grades have almost identical diamond content, though the particle size varies to some extent. The reason is that the cutting performance and wear resistance of the sintered diamond and surface finishing of the work are dictated by the diamond content. Sintered diamond blanks mostly consist of diamond layers less than 1mm thick on cemented carbide substrates and

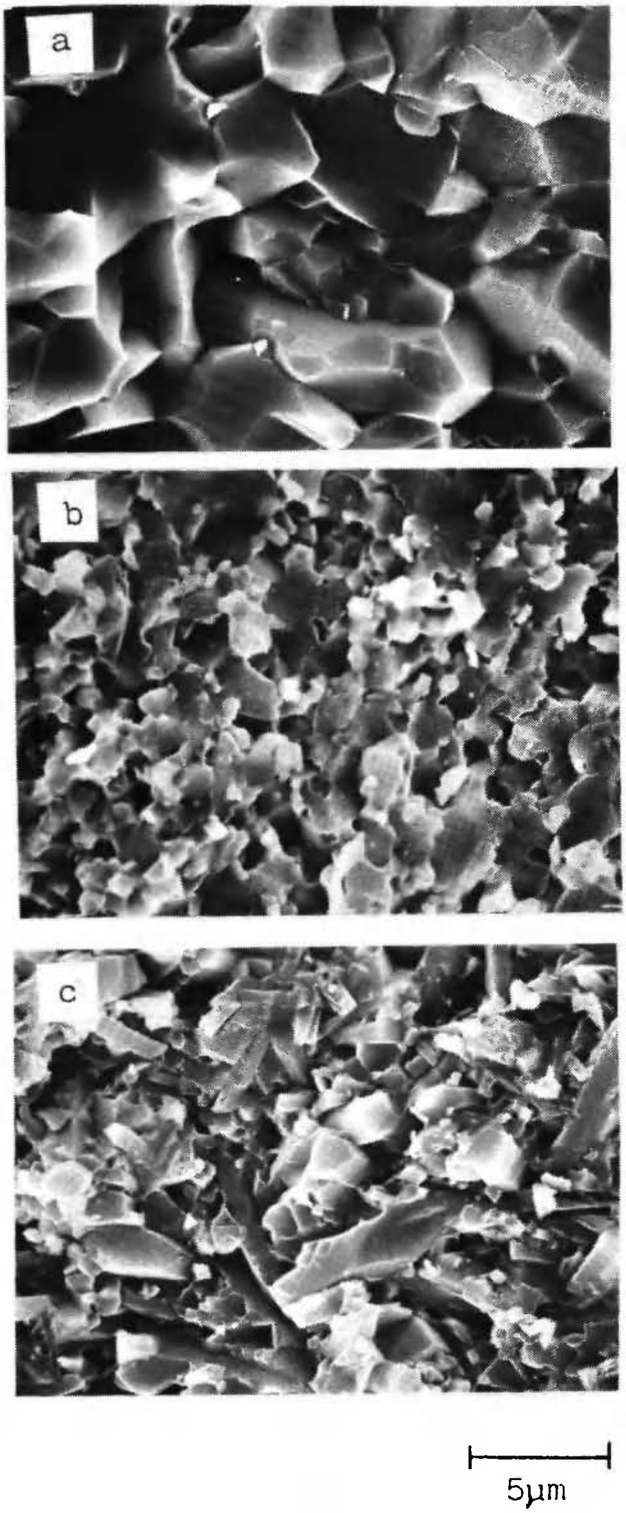


Fig. 11: Typical microstructure of ceramics. (a) Al_2O_3, (b) Al_2O_3-TiC, (c) Si_3N_4

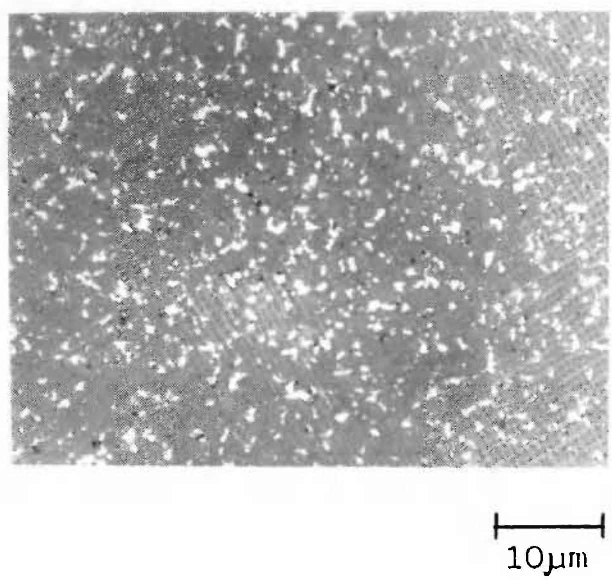


Fig. 12: Typical microstructure of sintered diamond.

are cut and brazed on carbide inserts or steel tool holders.

Advantages of sintered diamond over diamond single crystal are uniform mechanical properties, higher shock resistance and larger tool size. The mechanical properties of a single crystal vary for different crystal planes, while sintered diamond has uniform hardness and wear resistance in all directions. The diameter of sintered blanks was less than 10mm in the early stage, but now over 50mm diameter blanks are marketed.

The largest application of sintered diamonds is in cutting high silicon Al-Si alloys. Besides long tool life, fine surface finish is obtained because of low tool wear and minimum welding of works. Their tool life is tens to a hundred times longer than that of cemented carbides. Sintered diamonds also show superior performance in cutting other nonferrous alloys, soft and semi-sintered ceramics and cemented carbides, hard carbons, hard rubber, plastics and composite materials like FRPs, etc. On the other hand, diamond is not used in cutting iron group metals as it reacts with them at high temperature. The only exception is high carbon cast irons.

The other problems of sintered diamonds are tool price and grindability. The price is about 10 times higher than that of cemented carbides. Ultrahigh pressure sintering is a very high cost process and, in addition, grinding of sintered diamonds is an extremely time consuming process. These factors are mainly responsible for the high price. As the grinding is very difficult, re-grinding of sintered diamond tools is generally entrusted to the manufacturers or tool fabricators.

9. SINTERED CBN

CBN does not occur in nature. Sintered CBN was developed a little after sintered diamond employing a similar technology. The first sintered CBN was composed of about 90%CBN, the remainder being metal binder. Unlike sintered diamond, the present sintered CBNs are made with different CBN concentrations and different kinds of binders, though the first generation type is still in practical use. At present, the CBN content is changed within a wide range from about 50 to 90% and ceramic binders like TiC and TiN are more widely used than metallic ones. Examples of microstructure of sintered CBNs are shown in Fig. 13. The optimum CBN content, however, depends on the end application /16/. For example, a high CBN content is better in cutting super alloys and hardened HSS, while a longer tool life is obtained with a medium CBN in cutting hardened carbon steels and die steels. Higher CBN content generally increases chipping resistance.

CBN is more stable against reaction with iron group metals and, as a result, it is used in cutting super alloys, hardened steels and hard cast irons. Sintered CBN is replacing grinding wheels in machining hard ferrous alloys because of high productivity in cutting. On the contrary, CBN is sometimes replaced by less wear resistance but far cheaper ceramics on cost considerations.

Like sintered diamonds, sintered CBNs are also expensive and have poor grindability. Though their grindability is relatively better, common tool users still find it difficult to carry out regrinding.

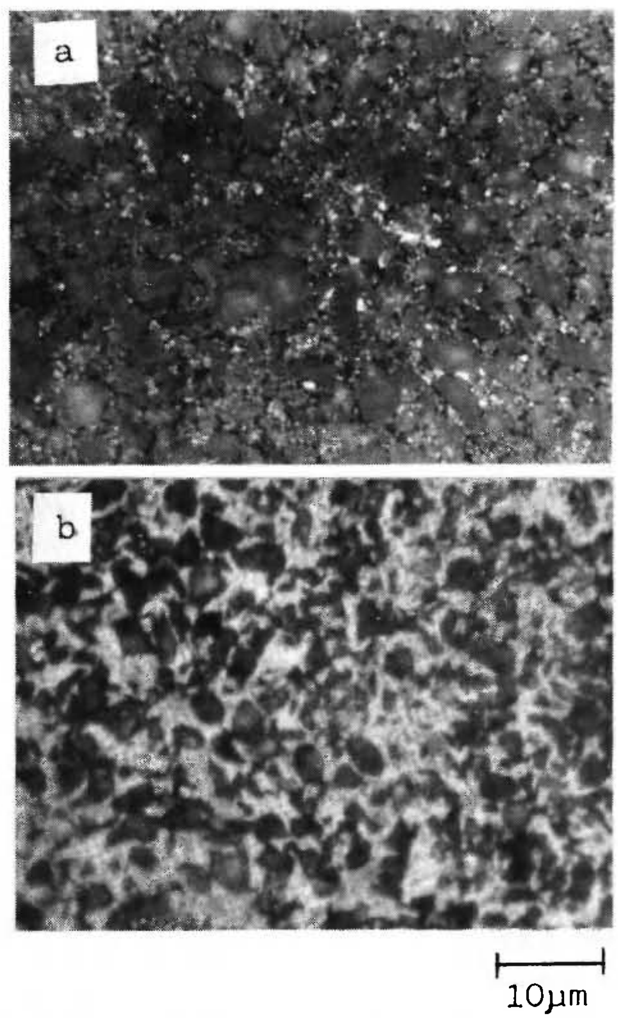


Fig. 13: Typical microstructure of sintered CBN. (a) 90%CBN, (b) 70%CBN

Applications of sintered diamonds and CBNs will widely expand if the grinding cost can be significantly reduced. A new grinding technology and the availability of suitable grinding wheels and machine tools are necessary to bring down this cost.

10. DIAMOND COATINGS

Recently, diamond coated cemented carbides, as shown in Fig. 14, have been projected as an alternative to sintered diamond for cutting tools. The expected advantages of diamond coatings over sintered diamond are large scale production, lower production cost, flexibility in tool shape like chip breakers, complex shape tools and so on. Synthesis of diamond from a gas phase has about 30 years of history /17/. But the present wide scale studies only started in 1982 and cover the development of diamond films deposited from CH_4 by hot filament CVD /18/ and microwave plasma CVD /19/ which were the turning point. Now many other deposition methods such as EACVD /20/, thermal plasma CVD /21/, gas torch /22/, etc. have bee proposed. Though CH_4 is the most common gas used, C_2H_5OH /23/, CO /24/, C_2H_2 /22/, etc. are also used as the source gases. The latest among practical applications of diamond films is, perhaps, in the production of diamond coated carbide cutting tools.

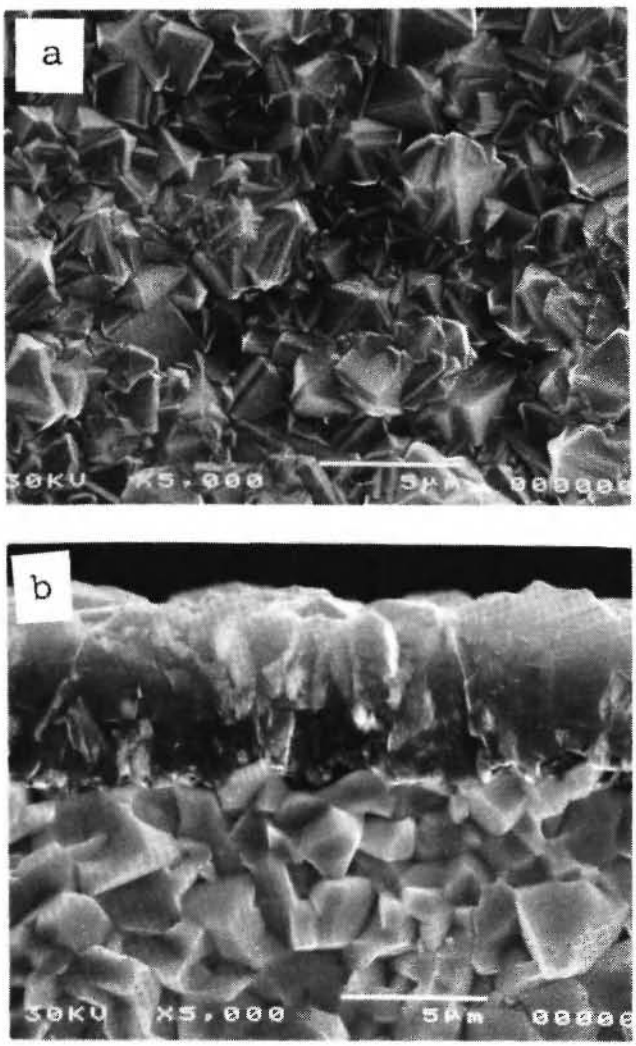


Fig. 14: Typical microstructure of diamond film. (a) surface, (b) cross section.

It is not very difficult to form a high purity diamond film on cemented carbides. However, the major problem in the case of cutting tools is the lack of adequate adhesion strength of the film to the substrate. Although to start with the films had only poor adhesion, and consequently spontaneously flaked off from the substrate, a number of improvements have since been effected particularly in surface pre-treatment technologies of the substrate. Today's diamond films are much improved and withstand to a fair extent even cutting a difficult-to-cut Al-20%Si alloy. A cutting test is exemplified in Fig. 15 /25/. A diamond coated cemented carbide shows excellent wear resistance and the tool life is prolonged more than several times compared to an uncoated substrate. The wear rate is almost the same for sintered diamond until film flaking occurs though it increases remarkably thereafter. Field tests for small scale practical use have already been started.

However, there remain some problems to be solved before full scale applications are possible. One is further improvement of adhesion strength to stand a longer cutting time, a higher cutting speed and interrupted cutting like milling. Also, coatings with uniform thickness and adequate adhesion on sharp cutting edges like drills, etc. have to be developed. Another problem is to achieve large scale coatings to improve productivity and thereby to reduce production costs. Increasing the coating area is not a simple matter. Experimental coatings up to now have been mostly produced using small systems capable of coating on areas corresponding to 30mm diameter. Recently, middle size microwave plasma CVD systems, for example 100mmØ, have been marketed. However, uniformity of the film, coating efficiency, etc. are not yet satisfactory. Technologies to improve the uniformity in plasma density, substrate temperature, etc. should be developed. In the case of hot filament CVD, the filament life should be prolonged in addition to the film uniformity.

11. CBN COATINGS

Potential demands for CBN coatings as an alternative to sintered CBN are larger than for diamond ones because they are expected to be used as tools for cutting steels and cast irons. Hard BN films have been developed by various methods such as ion beam deposition /26/, ion mixing /27/, laser deposition /28/, ion plating /29/ and plasma CVD /30/. An example of hard BN film is shown in Fig. 16. However, developments in this area are far slower than the progress in diamond coatings at present. The main reasons are difficulty in formation of high CBN film and inadequate adhesion strength. The nitrogen content is likely to be less than the stoichiometric value. The films are generally composed of CBN and amorphous BN with the CBN content less than 50%, although a few films /27/ with higher CBN content have been reported. The adhesion strength of all hard BN films are so poor that no visual effect of the coatings in cutting has been reported so far.

12. PROSPECT OF FUTURE MATERIALS

Development of new cutting tool materials with greater wear and chipping resistance at higher cutting speed and feed rate is an endless problem. It seems that there is at present little possibility of the discovery of a quite new hard, wear resistant substance suitable for cutting tools. However, further intensive developmental efforts can certainly bring about significant improvements in the existing materials. Strength and toughness can be increased by resorting to advanced alloy design technologies and production technologies. In addition to more uniform and defectless structure, reinforcements by whisker, etc. are expected. New surface modification technologies such as advanced coating, ion implantation, ion mixing and heat treatments in controlled atmosphere are expected to further improve the wear resistance of the materials. The grade and nature of cutting tool materials will become increasingly function-oriented and technologies will be developed to produce materials for specific requirements.

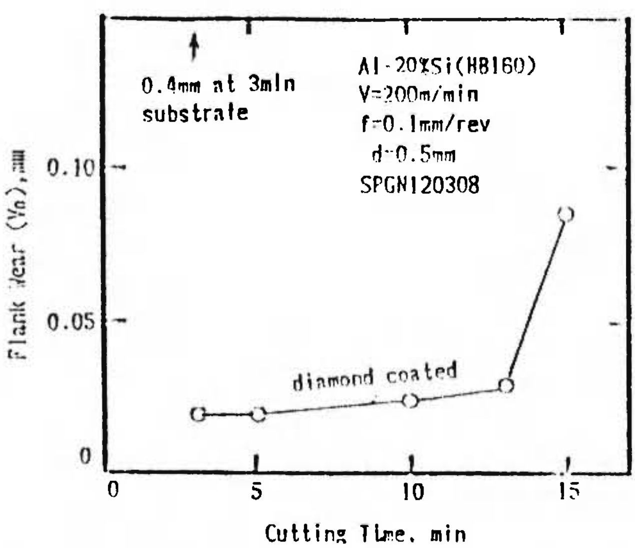


Fig. 15: The tool wear of diamond coated carbides in turning an Al-20%Si alloy.

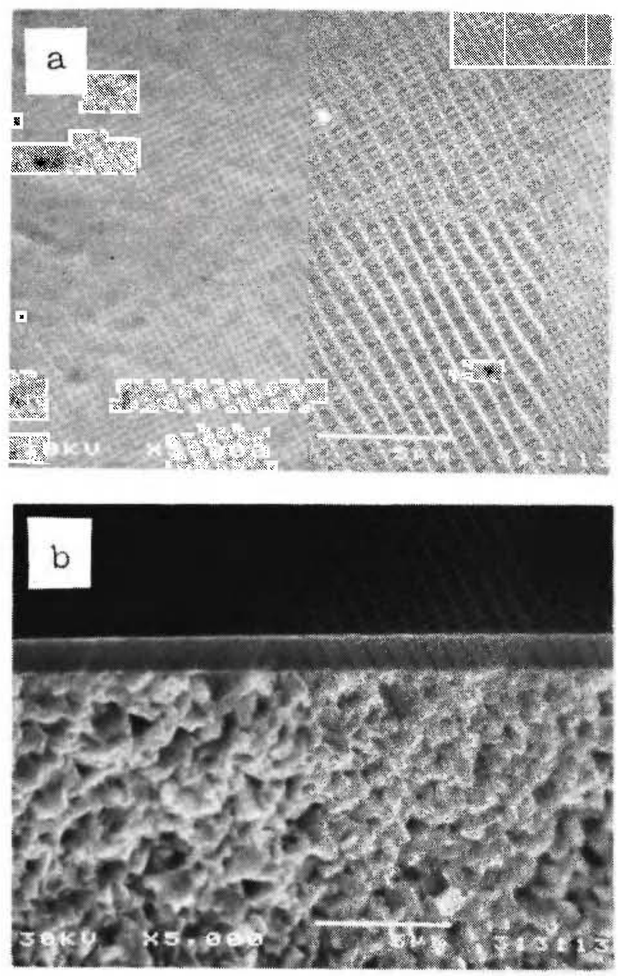


Fig. 16: An example of hard BN film.
(a) surface, (b) cross section.

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