

Module 3 Machinability

Version 2 ME, IIT Kharagpur

Lesson

16

Advanced Cutting Tool
Materials

Instructional Objectives

At the end of this lesson, the students will be able to

- (i) Classify, illustrate the properties and suggest the applications of the advanced cutting tool materials
 - (a) Coated carbides
 - (b) Cermets
 - (c) Coronite
 - (d) High Performance Ceramics (HPC)
 - (e) Cubic Boron Nitride (cBN)
 - (f) Diamond

(i) Development And Application Of Advanced Tool Materials

(a) Coated carbides

The properties and performance of carbide tools could be substantially improved by

- Refining microstructure
- Manufacturing by casting – expensive and uncommon
- Surface coating – made remarkable contribution.

Thin but hard coating of single or multilayers of more stable and heat and wear resistive materials like TiC, TiCN, TiOCN, TiN, Al₂O₃ etc on the tough carbide inserts (substrate) (Fig. 3.3.4) by processes like chemical Vapour Deposition (CVD), Physical Vapour Deposition (PVD) etc at controlled pressure and temperature enhanced MRR and overall machining economy remarkably enabling,

- reduction of cutting forces and power consumption
- increase in tool life (by 200 to 500%) for same V_c or increase in V_c (by 50 to 150%) for same tool life
- improvement in product quality
- effective and efficient machining of wide range of work materials
- pollution control by less or no use of cutting fluid

through

- reduction of abrasion, adhesion and diffusion wear
- reduction of friction and BUE formation
- heat resistance and reduction of thermal cracking and plastic deformation

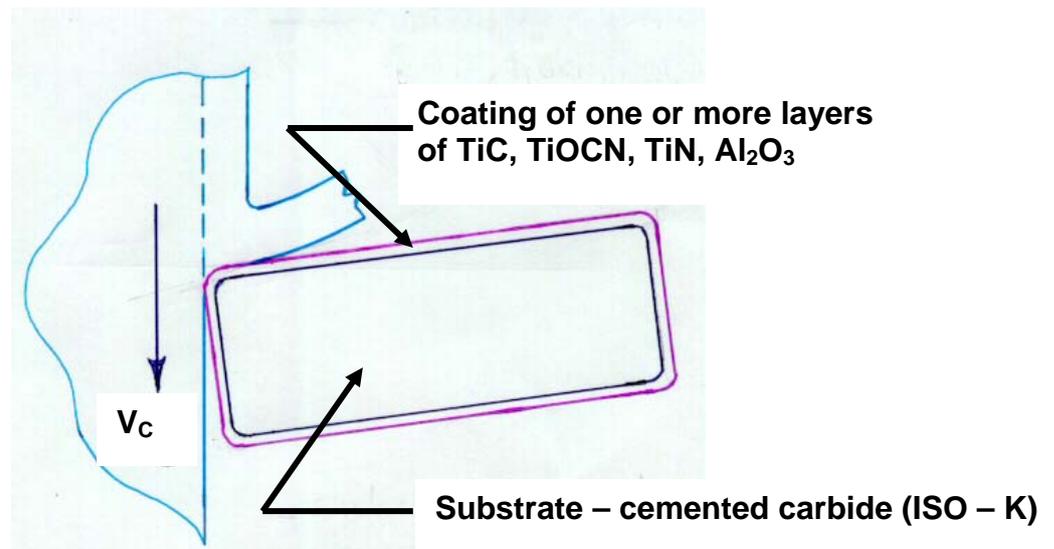


Fig. 3.3.4 Machining by coated carbide insert.

The contributions of the coating continues even after rupture of the coating as indicated in Fig. 3.3.5.

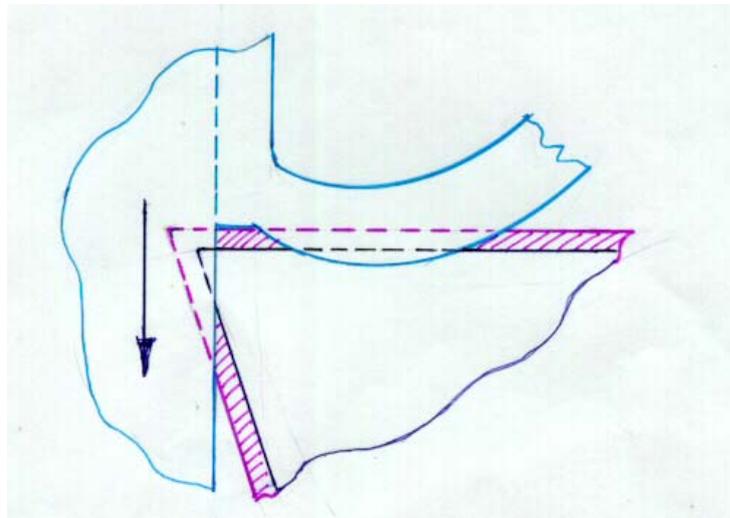


Fig. 3.3.5 Role of coating even after its wear and rupture

The cutting velocity range in machining mild steel could be enhanced from 120 ~ 150 m/min to 300 ~ 350 m/min by properly coating the suitable carbide inserts.

About 50% of the carbide tools being used at present are coated carbides which are obviously to some extent costlier than the uncoated tools.

Different varieties of coated tools are available. The appropriate one is selected depending upon the type of the cutting tool, work material and the desired productivity and product quality.

The properties and performances of coated inserts and tools are getting further improved by;

- △ Refining the microstructure of the coating
- △ Multilayering (already upto 13 layers within 12 ~ 16 μm)

- △ Direct coating by TiN instead of TiC, if feasible
- △ Using better coating materials.

(b) Cermets

These sintered hard inserts are made by combining 'cer' from ceramics like TiC, TiN or (or)TiCN and 'met' from metal (binder) like Ni, Ni-Co, Fe etc. Since around 1980, the modern cermets providing much better performance are being made by TiCN which is consistently more wear resistant, less porous and easier to make. The characteristic features of such cermets, in contrast to sintered tungsten carbides, are :

- The grains are made of TiCN (in place of WC) and Ni or Ni-Co and Fe as binder (in place of Co)
- Harder, more chemically stable and hence more wear resistant
- More brittle and less thermal shock resistant
- Wt% of binder metal varies from 10 to 20%
- Cutting edge sharpness is retained unlike in coated carbide inserts
- Can machine steels at higher cutting velocity than that used for tungsten carbide, even coated carbides in case of light cuts.

Application wise, the modern TiCN based cermets with bevelled or slightly rounded cutting edges are suitable for finishing and semi-finishing of steels at higher speeds, stainless steels but are not suitable for jerky interrupted machining and machining of aluminium and similar materials. Research and development are still going on for further improvement in the properties and performance of cermets.

(c) Coronite

It is already mentioned earlier that the properties and performance of HSS tools could have been sizeably improved by refinement of microstructure, powder metallurgical process of making and surface coating. Recently a unique tool material, namely Coronite has been developed for making the tools like small and medium size drills and milling cutters etc. which were earlier essentially made of HSS. Coronite is made basically by combining HSS for strength and toughness and tungsten carbides for heat and wear resistance. Microfine TiCN particles are uniformly dispersed into the matrix.

Unlike a solid carbide, the coronite based tool is made of three layers;

- the central HSS or spring steel core
- a layer of coronite of thickness around 15% of the tool diameter
- a thin (2 to 5 μm) PVD coating of TiCN.

Such tools are not only more productive but also provides better product quality.

The coronite tools made by hot extrusion followed by PVD-coating of TiN or TiCN outperformed HSS tools in respect of cutting forces, tool life and surface finish.

(d) High Performance ceramics (HPC)

Ceramic tools as such are much superior to sintered carbides in respect of hot hardness, chemical stability and resistance to heat and wear but lack in fracture toughness and strength as indicated in Fig. 3.3.6.

Through last few years remarkable improvements in strength and toughness and hence overall performance of ceramic tools could have been possible by several means which include;

- Sinterability, microstructure, strength and toughness of Al_2O_3 ceramics were improved to some extent by adding TiO_2 and MgO
- Transformation toughening by adding appropriate amount of partially or fully stabilised zirconia in Al_2O_3 powder
- Isostatic and hot isostatic pressing (HIP) – these are very effective but expensive route

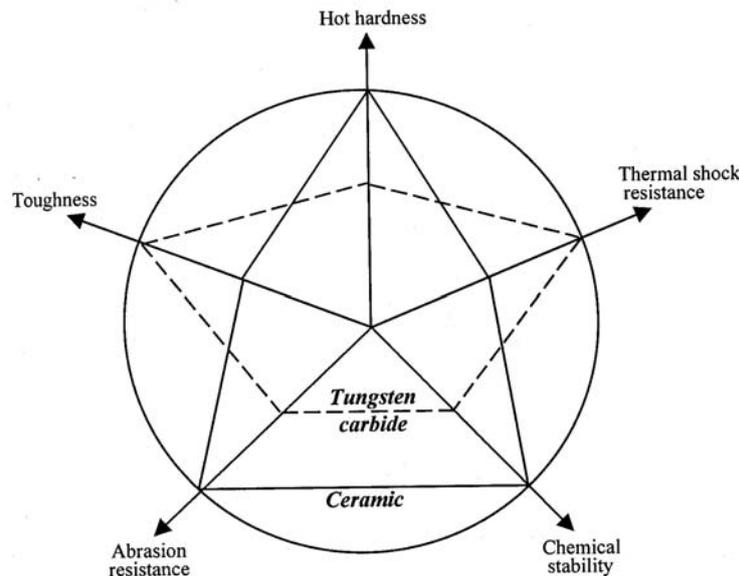


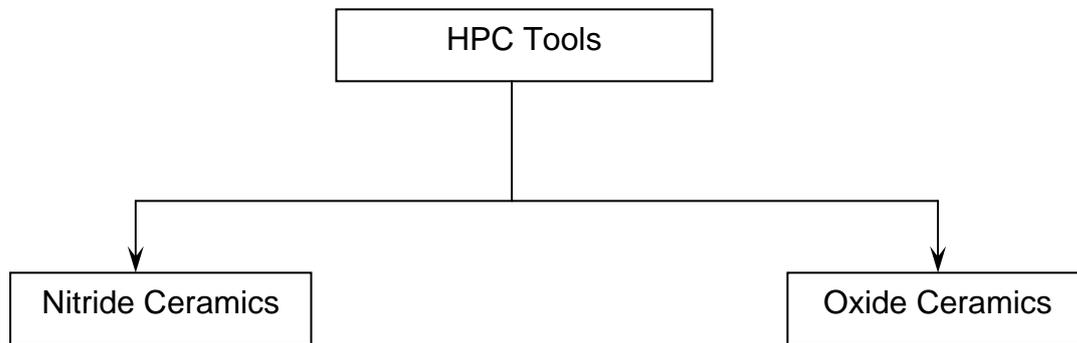
Fig. 3.3.6 Comparison of important properties of ceramic and tungsten carbide tools

- Introducing nitride ceramic (Si_3N_4) with proper sintering technique – this material is very tough but prone to built-up-edge formation in machining steels
- Developing SIALON – deriving beneficial effects of Al_2O_3 and Si_3N_4
- Adding carbide like TiC (5 ~ 15%) in Al_2O_3 powder – to impart toughness and thermal conductivity
- Reinforcing oxide or nitride ceramics by SiC whiskers, which enhanced strength, toughness and life of the tool and thus productivity spectacularly. But manufacture and use of this unique tool need specially careful handling
- Toughening Al_2O_3 ceramic by adding suitable metal like silver which also impart thermal conductivity and self lubricating property; this novel and inexpensive tool is still in experimental stage.

The enhanced qualities of the unique high performance ceramic tools, specially the whisker and zirconia based types enabled them machine structural steels at speed even beyond 500 m/min and also intermittent cutting at reasonably high speeds, feeds and depth of cut. Such tools are also found to machine relatively harder and stronger steels quite effectively and economically.

The successful and commonly used high performance ceramic tools have been discussed here :

The HPC tools can be broadly classified into two groups as :



Silicon Nitride

- (i) Plain
- (ii) SIALON
- (iii) Whisker toughened

Alumina toughened by

- (i) Zirconia
- (ii) SiC whiskers
- (iii) Metal (Silver etc)

Nitride based ceramic tools

Plain nitride ceramics tools

Compared to plain alumina ceramics, Nitride (Si_3N_4) ceramic tools exhibit more resistance to fracturing by mechanical and thermal shocks due to higher bending strength, toughness and higher conductivity. Hence such tool seems to be more suitable for rough and interrupted cutting of various material excepting steels, which cause rapid diffusional wear and BUE formation. The fracture toughness and wear resistance of nitride ceramic tools could be further increased by adding zirconia and coating the finished tools with high hardness alumina and titanium compound.

Nitride ceramics cannot be easily compacted and sintered to high density. Sintering with the aid of 'reaction bonding' and 'hot pressing' may reduce this problem to some extent.

SIALON tools

Hot pressing and sintering of an appropriate mix of Al_2O_3 and Si_3N_4 powders yielded an excellent composite ceramic tool called SIALON which are very hot hard, quite tough and wear resistant. These tools can machine steel and cast irons at high speeds (250 – 300 m/min). But machining of steels by such tools at too high speeds reduces the tool life by rapid diffusion.

SiC reinforced Nitride tools

The toughness, strength and thermal conductivity and hence the overall performance of nitride ceramics could be increased remarkably by adding SiC whiskers or fibers in 5 – 25 volume%. The SiC whiskers add fracture toughness mainly through crack bridging, crack deflection and fiber pull-out.

Such tools are very expensive but extremely suitable for high production machining of various soft and hard materials even under interrupted cutting.

Zirconia (or Partially stabilized Zirconia) toughened alumina (ZTA) ceramic

The enhanced strength, TRS and toughness have made these ZTAs more widely applicable and more productive than plain ceramics and cermets in machining steels and cast irons. Fine powder of partially stabilised zirconia (PSZ) is mixed in proportion of ten to twenty volume percentage with pure alumina, then either cold pressed and sintered at 1600 – 1700°C or hot isostatically pressed (HIP) under suitable temperature and pressure. The phase transformation of metastable tetragonal zirconia (t-Z) to monoclinic zirconia (m-Z) during cooling of the composite ($\text{Al}_2\text{O}_3 + \text{ZrO}_2$) inserts after sintering or HIP and during polishing and machining imparts the desired strength and fracture toughness through volume expansion (3 – 5%) and induced shear strain (7%). The mechanisms of toughening effect of zirconia in the basic alumina matrix are stress induced transformation toughening as indicated in Fig. 3.3.7 and microcrack nucleation toughening.

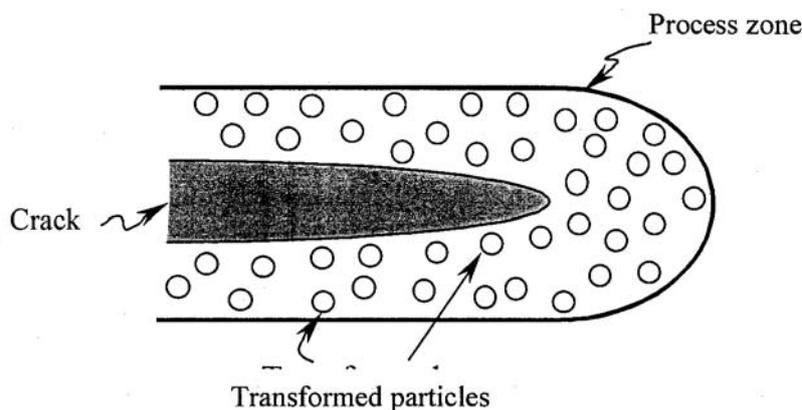


Fig. 3.3.7 The method of crack shielding by a transformation zone.

Their hardness have been raised further by proper control of particle size and sintering process. Hot pressing and HIP raise the density, strength and hot hardness of ZTA tools but the process becomes expensive and the tool performance degrades at lower cutting speeds. However such ceramic tools can machine steel and cast iron at speed range of 150 – 500 m/min.

Alumina ceramic reinforced by SiC whiskers

The properties, performances and application range of alumina based ceramic tools have been improved spectacularly through drastic increase in fracture toughness (2.5 times), TRS and bulk thermal conductivity, without sacrificing hardness and wear resistance by mechanically reinforcing the brittle alumina matrix with extremely strong and stiff silicon carbide whiskers. The randomly oriented, strong and thermally conductive whiskers enhance the strength and toughness mainly by crack deflection and crack-bridging and also by reducing the temperature gradient within the tool. After optimization of the composition, processing and the tool geometry, such tools have been

found to effectively and efficiently machine wide range of materials, over wide speed range (250 – 600 m/min) even under large chip loads. But manufacturing of whiskers need very careful handling and precise control and these tools are costlier than zirconia toughened ceramic tools.

Silver toughened alumina ceramic

Toughening of alumina with metal particle became an important topic since 1990 though its possibility was reported in 1950s. Alumina-metal composites have been studied primarily using addition of metals like aluminium, nickel, chromium, molybdenum, iron and silver. Compared to zirconia and carbides, metals were found to provide more toughness in alumina ceramics. Again compared to other metal-toughened ceramics, the silver-toughened ceramics can be manufactured by simpler and more economical process routes like pressureless sintering and without atmosphere control. All such potential characteristics of silver-toughened alumina ceramic have already been exploited in making some salient parts of automobiles and similar items. Research is going on to develop and use silver-toughened alumina for making cutting tools like turning inserts.. The toughening of the alumina matrix by the addition of metal occurs mainly by crack deflection and crack bridging by the metal grains as schematically shown in Fig. 3.3.8. Addition of silver further helps by increasing thermal conductivity of the tool and self lubrication by the traces of the silver that oozes out through the pores and reaches at the chip-tool interface. Such HPC tools can suitably machine with large MRR and V_C (250 – 400 m/min) and long tool life even under light interrupted cutting like milling. Such tools also can machine steels at speed from quite low to very high cutting velocities (200 to 500 m/min).

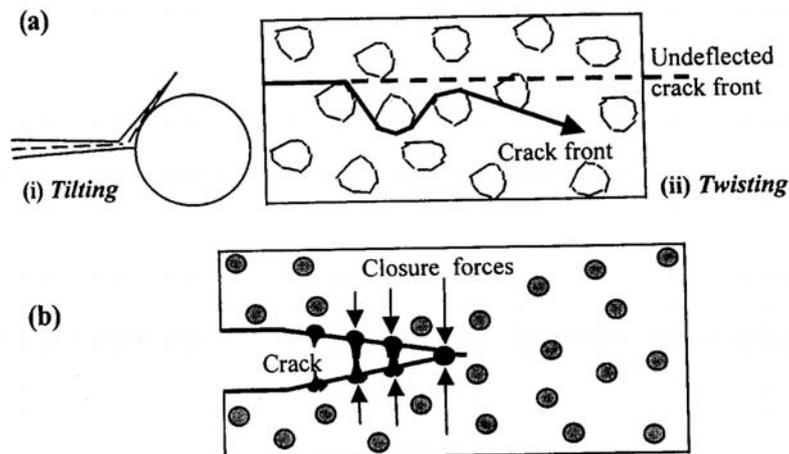


Fig. 3.3.8 Toughening mechanism of alumina by metal dispersion.

(e) Cubic Boron Nitride

Next to diamond, cubic boron nitride is the hardest material presently available. Only in 1970 and onward cBN in the form of compacts has been introduced as cutting tools. It is made by bonding a 0.5 – 1 mm layer of polycrystalline cubic boron nitride to cobalt based carbide substrate at very high temperature and pressure. It remains inert and retains high hardness and

fracture toughness at elevated machining speeds. It shows excellent performance in grinding any material of high hardness and strength. The extreme hardness, toughness, chemical and thermal stability and wear resistance led to the development of cBN cutting tool inserts for high material removal rate (MRR) as well as precision machining imparting excellent surface integrity of the products. Such unique tools effectively and beneficially used in machining wide range of work materials covering high carbon and alloy steels, non-ferrous metals and alloys, exotic metals like Ni-hard, Inconel, Nimonic etc and many non-metallic materials which are as such difficult to machine by conventional tools. It is firmly stable at temperatures upto 1400° C. The operative speed range for cBN when machining grey cast iron is 300 ~ 400 m/min. Speed ranges for other materials are as follows :

- Hard cast iron (> 400 BHN) : 80 – 300 m/min
- Superalloys (> 35 R_C) : 80 – 140 m/min
- Hardened steels (> 45 R_C) : 100 – 300 m/min

In addition to speed, the most important factor that affects performance of cBN inserts is the preparation of cutting edge. It is best to use cBN tools with a honed or chamfered edge preparation, especially for interrupted cuts. Like ceramics, cBN tools are also available only in the form of indexable inserts. The only limitation of it is its high cost.

(f) Diamond Tools

Single stone, natural or synthetic, diamond crystals are used as tips/edge of cutting tools. Owing to the extreme hardness and sharp edges, natural single crystal is used for many applications, particularly where high accuracy and precision are required. Their important uses are :

- Single point cutting tool tips and small drills for high speed machining of non-ferrous metals, ceramics, plastics, composites, etc. and effective machining of difficult-to-machine materials
- Drill bits for mining, oil exploration, etc.
- Tool for cutting and drilling in glasses, stones, ceramics, FRPs etc.
- Wire drawing and extrusion dies
- Superabrasive wheels for critical grinding.

Limited supply, increasing demand, high cost and easy cleavage of natural diamond demanded a more reliable source of diamond. It led to the invention and manufacture of artificial diamond grits by ultra-high temperature and pressure synthesis process, which enables large scale manufacture of diamond with some control over size, shape and friability of the diamond grits as desired for various applications.

Polycrystalline Diamond (PCD)

The polycrystalline diamond (PCD) tools consist of a layer (0.5 to 1.5 mm) of fine grain size, randomly oriented diamond particles sintered with a suitable binder (usually cobalt) and then metallurgically bonded to a suitable substrate like cemented carbide or Si₃N₄ inserts. PCD exhibits excellent wear resistance, hold sharp edge, generates little friction in the cut, provide high fracture strength, and had good thermal conductivity. These properties contribute to PCD tooling's long life in conventional and high speed machining of soft, non-ferrous materials (aluminium, magnesium, copper etc), advanced composites and metal-matrix composites, superalloys, and non-metallic materials. PCD is particularly well suited for abrasive materials (i.e. drilling

and reaming metal matrix composites) where it provides 100 times the life of carbides. PCD is not usually recommended for ferrous metals because of high solubility of diamond (carbon) in these materials at elevated temperature. However, they can be used to machine some of these materials under special conditions; for example, light cuts are being successfully made in grey cast iron. The main advantage of such PCD tool is the greater toughness due to finer microstructure with random orientation of the grains and reduced cleavage. But such unique PCD also suffers from some limitations like :

- High tool cost
- Presence of binder, cobalt, which reduces wear resistance and thermal stability
- Complex tool shapes like in-built chip breaker cannot be made
- Size restriction, particularly in making very small diameter tools

The above mentioned limitations of polycrystalline diamond tools have been almost overcome by developing Diamond coated tools.

Diamond coated carbide tools

Since the invention of low pressure synthesis of diamond from gaseous phase, continuous effort has been made to use thin film diamond in cutting tool field. These are normally used as thin (<50 μm) or thick (> 200 μm) films of diamond synthesised by CVD method for cutting tools, dies, wear surfaces and even abrasives for Abrasive Jet Machining (AJM) and grinding. Thin film is directly deposited on the tool surface. Thick film (> 500 μm) is grown on an easy substrate and later brazed to the actual tool substrate and the primary substrate is removed by dissolving it or by other means. Thick film diamond finds application in making inserts, drills, reamers, end mills, routers. CVD coating has been more popular than single diamond crystal and PCD mainly for :

- Free from binder, higher hardness, resistance to heat and wear more than PCD and properties close to natural diamond
- Highly pure, dense and free from single crystal cleavage
- Permits wider range of size and shape of tools and can be deposited on any shape of the tool including rotary tools
- Relatively less expensive

However, achieving improved and reliable performance of thin film CVD diamond coated tools; (carbide, nitride, ceramic, SiC etc) in terms of longer tool life, dimensional accuracy and surface finish of jobs essentially need :

1. good bonding of the diamond layer
2. adequate properties of the film, e.g. wear resistance, micro-hardness, edge coverage, edge sharpness and thickness uniformity
3. ability to provide work surface finish required for specific applications.

While cBN tools are feasible and viable for high speed machining of hard and strong steels and similar materials, Diamond tools are extremely useful for machining stones, slates, glass, ceramics, composites, FRPs and non ferrous metals specially which are sticky and BUE former such as pure aluminium and its alloys.

CBN and Diamond tools are also essentially used for ultraprecision as well as micro and nano machining.