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Cutting tools and applications

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ABSTRACT

Cutting tools are one of the basic elements of modern industrial production, providing high efficiency and precision in machining different materials. This article examines the basic materials such as high-speed steels, stellites, hard metals and cermets, which are frequently used in cutting tool technologies, and their applications in machining processes. High speed steels (HSS) are preferred in a comprehensive scope of purposes owing to their superior wear resistance and impact resistance. These steels, enhanced with alloying elements such as carbon, vanadium and molybdenum, are widely used in machine tools operating at low speeds. Stellites are generally cobalt-based alloys that stand out with their high hardness and corrosion resistance. These materials are preferred in special applications by maintaining wear resistance even at high temperatures. Hard metals consist of components such as tungsten carbide (WC) and offer excellent performance at high cutting speeds. These materials are widely used in sectors requiring precision machining such as automotive and aerospace. Cermets are a combination of ceramic and metal phases and combine high hardness with chemical stability. It is especially preferred in applications where fine stock removal and surface quality are important. As a result, each cutting tool material offers specific advantages and limitations depending on the application requirements. The right material selection optimizes tool life and workpiece surface quality while increasing production efficiency.

Keywords: Cutting tools, Applications, Coatings, Machining, Tool wear

1. Introduction

The range of materials available for cutting has been constantly evolving since the 1920s. We now have the choice of an expansive range of cutting objects. The market acceptance of indexable insert tools in the 1960s brought enormous advantages to machine tool operators. Direct pressing techniques empowered the fabrication of highly developed chip channels in indexable inserts. Such channels are not viable to reproduce by grinding and are moreover very expensive. Solitary of the most significant developments in cutting objects was the growth of ‘coated’ indexable insertions. These were initially launched in 1969. The recent generation of coated inserts provided productivity gains never foreseen at the time of their original advancement. The tool holders that hold indexable inserts have also undergone significant change since the 1960s. Clamping arrangements have shifted from ‘finger’ mode clamping, which frequently impedes chip movement, to clutching by pins, levers or special screws inserted into the center dip in the insert [1], [2]. Automated instrument altering has become the model in prevailing machine tools, and several excellent systems are in undertaking wherever the tool skull is changed from a turret deprived of any worker intervention.

Workpiece items are another crucial issue in machining. For example, in no case should diamond be used for machining steel, or ceramic be chosen for a workpiece that will require heavy interrupted cuts. This work aims to provide information on turning, drilling, splitting, grooving, stringing, milling, and boring.

2. Cutting substances

The material used for cutting the metal must withstand the equipment of the cutting process. There are three basic problems in the cutting process:

a) Wear on the cutting edge, b) Heat generated to remove the material, c) Shock generated during cutting.

Therefore, the belongings that the cutting substance must have been in this manner:

a) Hardness against wear, b) Thermal resistance, c) Adequate strength to endure tremor throughout cutting.

High Speed Steels, Hard metals, Cermets, Sialons, Ceramics, Silicon Nitride and Diamond are used for cutting.

As it is known, increasing hardness causes a decrease in toughness and materials with high hardness fail due to fracture in workpieces with holes.

Silicon nitride and Sialons are included in ceramics. There are two mostly recognized ensembles of ceramics and these are silicon-based ceramics and aluminum oxide-based ceramics [1], [3].

2.1 High speed steels

High-speed-steels (HSS) offer the highest toughness but smallest hardness among cutting materials, with hardness achieved through heat treatment. They soften at temperatures above 600°C, limiting cutting speeds to around 50 m/min [1], [4]. Several high-speed tool steels are shown in Figure 1.

Fig 1. Various high speed tool steels

Applications of HSS can be applied for turning, drilling and milling as follows:

- Turning: Used mainly in automatic screw machines for high-volume part production.
- Drilling: Accounts for 80% of all drilling operations, ideal for machines with low power and hardness limitations.
- Milling: Widely used in solid end mills, slot drills, and face milling cutters, making up 40% of the milling cutter marketplace.

Key Advancements can be obtained via TiN coating. In Titanium Nitride (TiN) coating, a thin (3-micron) gold-colored coating applied via Physical Vapor Deposition (PVD) increases cutting speed and feed rates without compromising hardness.

Types of HSS are T, M and Co containing series as shown as follows:

1. T-Series: Tungsten-based, easier to heat treat but less hard.
2. M-Series: Molybdenum-based, more commonly used for drills and end mills.
3. Cobalt-Containing: Increases hot hardness and wear resistance, ideal for machining hard steels (e.g., M42 for heat-resistant alloys).

Common Alloys of HSS are M2, T42, M42 & M35 and they are shown as follows:

- M2: Most popular for drills and taps.
- T42: Used for applications requiring high wear resistance.
- M42 & M35: Preferred for coated inserts and machining heat-resistant alloys.

Typical hardness of HSS is about 62–68 Rockwell C (800–900 VDH), with harder grades like T42 reaching ~1000 VDH. Main applications of HSS are drilling, milling, slot drills, taps, reamers, broaches, dovetail form tools, and regrindable tool bits for smaller lathes (Table 1).

Table 1. Cutting tools from tool steels [5]

Properties and steel types	**Young modulus (GPa)**	**Compressive Strength (MPa)**	**Fracture toughness (MPa.m $^{0.5}$)**	**Service Temperature (ºC)**
AISI M10 (high speed)	220	2200	19	Max: 555 Min: -60
AISI M47 (high speed)	225	2600	16.6	Max: 540 Min: -63
AISI S6 (shock resisting)	210	1700	23.3	Max: 190 Min: -63
AISI T5 (high speed)	240	2190	19.6	Max: 555 Min: -63
AISI M4 (high speed)	233	2200	18.5	Max: 555 Min: -63
AISI M42 (high speed)	226	2600	16.6	Max: 525 Min: -63
AISI T15 (high speed)	230	2410	17.6	Max: 555 Min: -63
AISI S7 (shock resisting)	201	380	56	Max: 575 Min: -63
AISI W5 (water hardening)	210	1850	22.4	Max: 190 Min: -63
AISI A6 (air hardening cold work)	210	2100	19.6	Max: 165 Min: -63
AISI O6 (oil hardening cold work)	209	2035	20.6	Max: 190 Min: -63
AISI A2 (air hardening cold work)	214	1970	20.8	Max: 190 Min: -63
AISI O7 (oil hardening cold work)	210	2075	20.0	Max: 190 Min: -63

2.2 Stellite

Stellite is a cobalt-based alloy that achieves its hardness without heat treatment. The primary grade used in cutting is Stellite Alloy No. 100, composed of cobalt (Co), chromium (Cr), tungsten (W), and carbon (C). It offers superior hot hardness (535 VDH at 700°C) compared to high-speed steel (175 VDH) [1], [6].

Properties of Stellite Alloy No. 100 are as follows: Components: 34% Cr, 19% W, 2% C, remainder Co. Its hardness is ~950 VDH; and density is 8.75 g/cm³

Stellite can ve used for turning and cutting applications. Turning Operations are ideal for machining hard-to-cut surfaces like welds, which are irregular, hard, and prone to causing interrupted cuts. On the other hand stellite operates at medium to low cutting speeds, slightly higher than high-speed steel but lower than hard metals. Stellite is used in niche applications with limited importance in modern machining due to its narrow performance range.

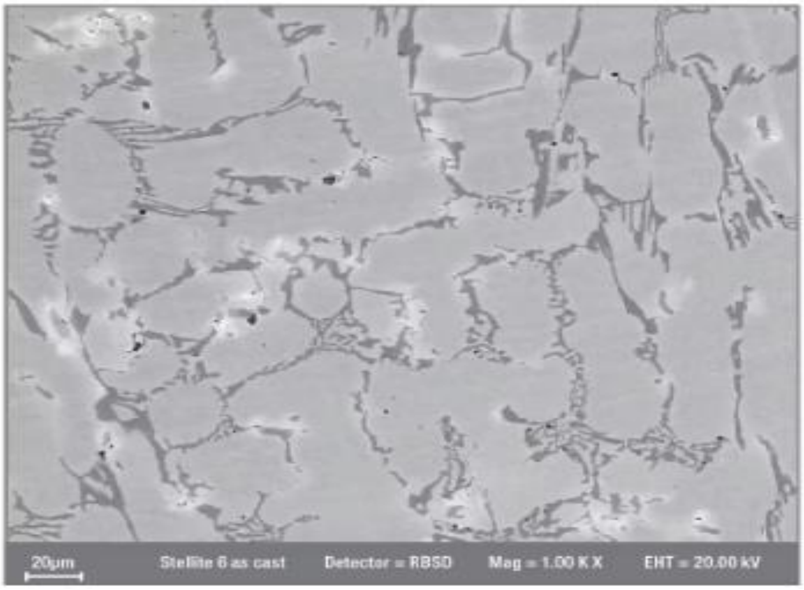

Figure 2. SEM microstructure Stellite 6 at 1000X enlargement [1]

2.3 Hard metals

Hard metals, primarily tungsten carbide (WC) bonded with cobalt (Co), are the core of modern cutting materials. They offer a balance between wear and shock resistance, depending on cobalt content and WC grain size [1], [7].

ISO Classification (ISO RS13) of hard metals are as follows:

- K (Red): Cast irons, non-ferrous metals.
- P (Blue): Steels.
- M (Yellow): Heat-resistant alloys.

Composition and Properties of WC-Co alloys from hard metals are as follows:

  - Hardness: 1250–1800 VDH.
  - Co content: 5–12% by weight.
  - Grain size: 0.5–5 µm.

Increasing Co improves toughness but reduces hardness. Fine-grained WC increases hardness but reduces toughness. The functional scale of Co content for cutting functions is about 5% to 12% by weight. Grain dimensions of WC range from about 0.5 micrometers to 5 micrometers. The hardness range of those alloys is from 1250 VDH to 1800 VDH. The microstructure of the 6Co- 94WC hard metal is shown in Figure 3.

In the case of adding TiC, TaC or NbC, wear resistance of hard metals is increased as follows.

1. TiC Addition:
    - Improves wear resistance and prevents cratering when cutting steels.
    - Added in amounts from 5% to 25% by weight.
2. TaC and NbC Addition:
    - Enhances hot hardness and prevents plastic deformation.
    - TaC is often diluted with NbC to reduce cost.

Applications of hard metals are shown as follows:

- K Grades: Used for machining stainless steels (austenitic), cast irons, and non-ferrous metals, requiring higher Co content for toughness.
- M Grades: Used for heat-resistant alloys, with 6–9% Co and 4–8% TiC, offering a hardness of 1450–1650 VDH.

Coated Hard Metals are summarised as follows: Recent advancements include thin coatings like TiC, TiN, TiCN, and Al_2O_3, significantly improving cutting performance and productivity. Approximately 70% of all turning operations use hard metal tooling, especially coated inserts.

In summary, hard metals are essential for a wide range of machining treatments, offering a versatile solution for high-speed, precision, and heavy-duty cutting tasks.

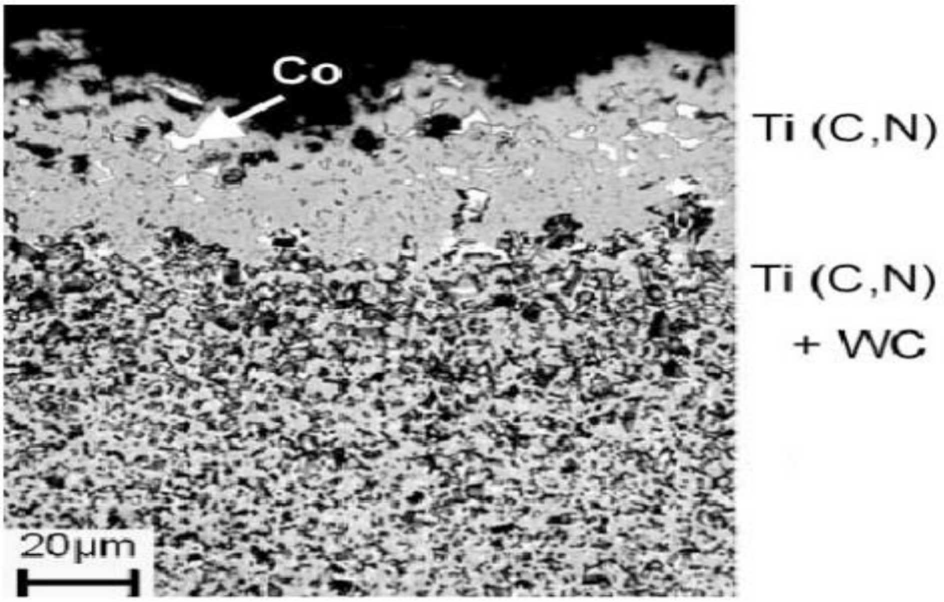

Figure 3. Micrograph of a (Ti,W)(C,N)/Co hard metal sintered at 1500 °C with 5 bar N 2 for 1 h [1]

This photomicrograph was taken at x 1500 magnification. The gray angular grains are WC and the grey environment is the Co binder metal. In this situation, the grain dimension of the WC is 1.5 micrometers on average and is called the medium grain size. In general, hard metals are known as 'cemented carbides'.

TaC has similarly been included in these TiC-comprising grades meanwhile the mid-1950s. It raises the hot hardness of the alloy, and this improves to stop permanent distortion of the sharp edge. Since TaC is costly, it is usually weakened with 50% NbC deprived of compromising the execution of the alloy.

A micrograph of one of these quintets of hard metals is flourished in Fig. 4 at x 1500 enlargement. The component of this alloy is 8.5% Co, 71.5% WC, 9% TiC and 11% TaNbC. It has a hardness of 1575 VDH and a mass of 12.4 g/cm3. The gaunt, more open grains are WC and the whitened environment is Co binder. The blacker and rounder grains are what is called a 'TiC merged crystal' or a solid solution of TaNbC + WC in TiC [1].

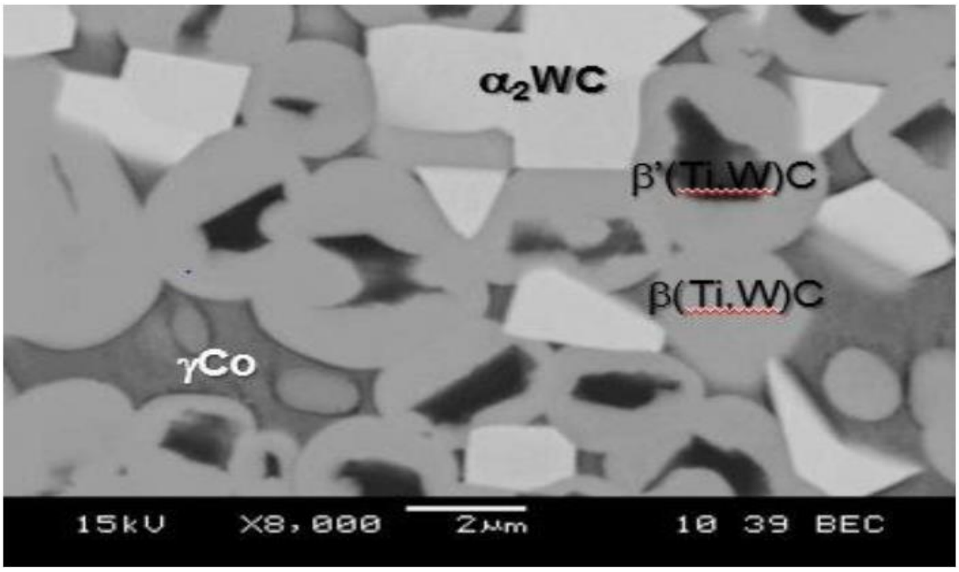

Figure 4. SEM micrograph of tested hard metals at various magnification 8000 [1]

The whole family of hard metals is generated by a PM (powder metallurgy) manner. The simple Co-WC alloys are completed by blending Co and WC powders, compressing the combination into forms and then sintering these models. If TiC is to be added to the alloy, it is excellent to improve it as a powder, which is a solid solution of WC in TiC. The subsequent alloy is harder than if TiC were included as an absolute powder.

The above information relates to normal hard metals. In the last two decades, considerable developments in chopping performance have been attained by employing very slender coverings such as TiC, TiN, TiCN, Al2O3, etc. In summary, hard metals involve an appropriate broad range of machining purposes. It is assessed that approximately 70% of entirely turning undertakings are performed via hard metal tooling. Coated hard metals on inserts allow very high levels of productivity to be achieved.

2.4 Cermets

Cermets are carbonitride-founded stuff. The soft Co phase and the hard TiCN phase form the cermet. TiCN grain sizes range from 0.5 to 2 microns. The density of cermets is about 6 g/cm3. Each producer has it concede compositions, and various contain carbides for instance Mo2C, WC and TaC. The hardness of those cermets is 1600 VDH. Cermets are used in Europe at 3% to 4%, while in Japan this figure is 25%. In summary, cermets are capable of high-speed machining. They implement well in light to medium cutting operations in equally turning and milling functions on steel work fragments [1], [8]. Several cermet tools are shown in Figure 5.

Fig 5. Several cermet tools

2.5 Ceramics (sialons, Al2O3, SiN)

2.5.1 Sialons

This slicing stuff can be classified as silicon nitride-grounded ceramics. Silica (Si02), alumina (Al203) and silicon nitride (Si3N4) powders are mixed with a modest amount of yttrium (Y203), then cool compressed and sintered. Through sintering, silica reduces with alumina and yttrium to compose a liquid. Sialons have a hardness of 1700 VDH and a density of 3.3 g/cm3. Sialons save their hardness safer than alumina at hotness between 800° and 1000°C. Sialons cannot be utilized for steel machining due to dissolution at high paces. The machining performance of hardened die steels is very effective. Cast irons can be machined at greater velocities than hard metals [9], [10], 11]. In summary, sialons are used for machining heat-resistant alloys. Cast irons accomplish well at superior cutting rates but are not appropriate for steel machining [1].

2.5.2 Aluminum oxide based ceramics

Heat is generated during machining in metal cutting. At 800°C, Al203 ceramics exhibit better mechanical possessions than hard metals. Below 8000°C, hard metals have excellent strength rivaled to ceramics. Tiles are satisfactory for machining gray cast iron in substantial mass fabrication. The hardness can be increased by adding 30-40% TiN or TiC to alumina. The increased hardness makes it suitable for machining harder steels.

A third type of ceramic is alumina/zirconium-based ceramics containing 25% silicon carbide (SiC) 'whiskers' to strengthen the structure [12], [13], [14]. In summary, alumina-based ceramics can be machined at advanced speeds and have a bigger hot hardness than hard metals [1].

2.5.3 Silicon nitride (Si3N4)

Si3N4 is also a ceramic utilized as a cutting substance and is produced by powder metallurgy method. A material with higher density and strength is obtained by hot pressing. Si3N4 is a cutting material with a hardness of 1800 VDH and a density of 3.2 g/cm3. Its grain dimensions are in the limit of 2 to 3 microns [1], [15], [16]. It has good wear and thermal shock resistance. In summary, silicon nitride has good toughness that allows milling and turning of gray cast iron. It should not be used to machine steels. In addition, the service temperatures and mechanical properties of some cutting tools made of tungsten carbides are given in Table 2.

Table 2. Cutting tools from tungsten carbides [5]

Properties and tungsten carbides	**Young modulus (GPa)**	**Compressive Strength (MPa)**	**Fracture toughness ($MPa.m^{0.5}$)**	**Service Temperature (°C)**
WC+Co (84.8)	540	4200	17.8	Max: 615 Min: -273
WC+Co (72)	480	3200	22.1	Max: 615 Min: -273
WC+Co (88)	580	4000	16	Max: 615 Min: -273
WC+Co (94.03)	690	5310	3.8	Max: 615 Min: -273
WC+Co (89.01)	580	6000	13	Max: 615 Min: -273
WC+C (69.5)	550	5110	10	Max: 615 Min: -273
WC+C (77.01)	550	5110	11	Max: 615 Min: -273
WC+TiC (69)	530	5310	9	Max: 615 Min: -273
WC+TiC (84.01)	600	5710	9	Max: 615 Min: -273
WC+Co (76.5)	560	5005	12	Max: 615 Min: -273
WC+Co (86)	590	5310	10	Max: 615 Min: -273
WC+Co (96)	670	7810	7	Max: 615 Min: -273
WC+Ni/Cr (91)	600	5005	11	Max: 570 Min: -273
W-Ni-Fe (CMW 3000)	335	553	135	Max: 928 Min: -273
W-Ni-Fe (ROSM WH9766F)	380	413	135	Max: 963 Min: -273
W-Ni-Cu (CMW 1000)	276	683	135	Max: 913 Min: -273
W-Ni-Mo-Fe (Anviloy 1150)	335	828	135	Max: 933 Min: -273
W-Re (W-25Re)	400	1590	135	Max: 913 Min: -273

3. Coatings

Coatings are diffusion barriers and have been used on HSS drills since 1969. The coats utilized are very hard (» 2500 VDH) and very wear challenging. Representative components of coats are TiN, Al203, TiC, and TiCN [1].

3.1 Single layer coatings

A TiC layer of 10 to 12 microns thick was the first coating by the CVD method. Through the accumulation route, some carbon was removed from the face of the hard metal as position of the covering, and this altered the carbon offset at the intersection of the covering and the hard metal substratum. This decrease in the carbon equilibrium resulted in the creation of a fragile combination at the interface relating the layer and the substratum.

TiN is an outstanding one film layer for high-speed steel, unlike hard metal. CVD coating is performed at a high temperature of 900°C, which causes the high-speed steel to make softer. Heat-up treatment can then be completed; however, distortion may occur. However, an alternative is PVD at 500°C, which preserves the hardness of the high-speed steel. This is an extremely popular technique for covering HSS drills with TiN. CVD coating provides a quicker deposition degree than PVD, and CVD coats are typically 5 to 12 microns thick. PVD coatings achieve a coating thickness of 3-5 microns [1].

3.2 Two and transition-layer coatings

In the first 1970s, the obstacle of coating devotion to hard metal was solved by employing a thin layer of TiC of 0.5 microns to the substrate. A subsequent coating of TiN or Al2O3 was then placed on the TiC layer. Two-layer structures with TiN on the exterior complete exceptionally fine in steels and extremely fine in cast irons.

Some hard metal manufacturers have claimed that there are stresses where two coating layers of TiC+TiN are joined. The medium permanent film of TiCN among TiC and TiN is recognized as the transition film [1].

Transition layer coatings are produced by the CVD process. In the CVD process, reactions occur over a wide range of warmth involving 750°C and 1050°C. If methane is replaced by nitrogen, titanium nitride is formed. If a combination of methane and nitrogen is applied, titanium carbonitride is created.

3.3 Multi-layer coatings

Later, multilayer coatings with a total thickness of 10 microns and up to eight layers were developed. These include TiC, TiN, TiCN and Sl2O3 layers [1]. A cross-section of such a part can be observed in Figure 6. The enlargement is x1500 and the width of this multilayer is 8 microns. All the Al2O3 levels are less than 1 micron meter thin and are confirmed by a TiN layer of comparable depth. This layered formation is excluding susceptible to fracture than a two-layer structure with the consistent entire depth. Such coatings must be deposited by CVD process.

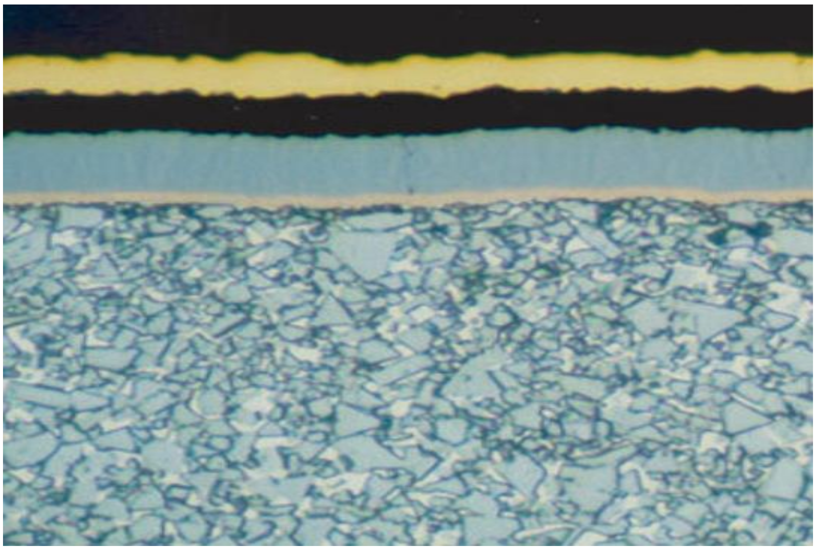

Figure 6. CVD multi-layer coating on WC-Co hard metal with TiN_{1-x} as upper and lower film [1]

Early coatings provided up to three times the performance improvement over uncoated hard metal. These more advanced coats provide up to nine times the improvement over standard hard metal.

4. Machining processes

4.1 Lathe tools

Rotary tools can be separated into three leading gathers. They are:
a) Tool inserts, High-Speed -Steel devices.
b) Brazed hard metal tools.
c) Tool holders.

High speed steel single-end turning utensils include solid high-speed-steel inserts for small tools, butt welded utensils with heads made of high-speed-steel and joined to a medium carbon steel shaft, and very large tools where the device tip is a part of high-speed-steel brazed to a steel shaft [1]. Various lathe cutting tools are shown in Figure 7.

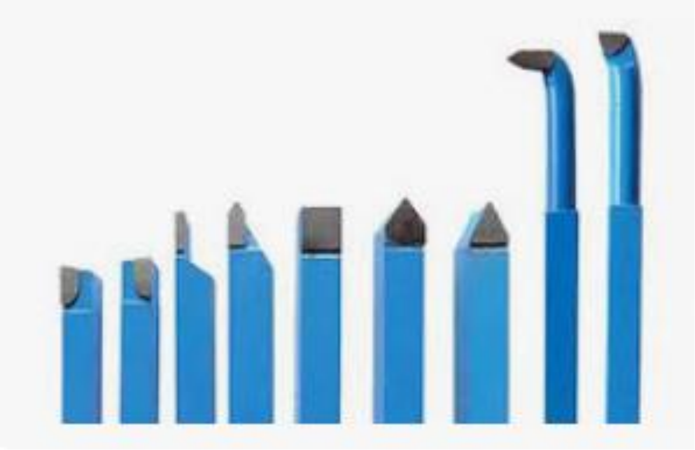

Fig 7. Numerous lathes cutting tools

For circular device inserts, eight diameters reaching from 4 to 20 mm and five lengths ranging from 63 mm to 200 mm are specified. Square section ground tool inserts choice from 4 x 4 to 25 x 25 mm and the intervals are the same as those used for circular piece tools and the length descriptions also apply. For rectangular piece tool inserts, seven section sizes of 4, 5, 6, 8, 10, 12 and 16 mm are specified. Peaks scale from 6 to 25 mm. Butt-welded high-speed-steel instruments were introduced in the immediate 1930s and are even operating at present. These are a British Standard, BS 1296. There is also a DIN standard that indicates instrument figures.

The British standard covers fifteen different butt-welded tool shapes and size tables are conferred for equally favored and non-favored sizes. These profiles include turning tools as well as drilling, parting, screw cutting, planning and reaming tools. Every tool shape is provided with a reference number. Stellite turning instruments are accessible as instrument inserts with cutting profiles. Tool inserts are solid stellite and tipped tools are produced from cast stellite tips brazed to steel shafts. The updated ISO 243, No.1 No.2 etc. Includes 6 outer turning instruments and 1 cutting tool, recognized as. Specifies the hard metal insert utilized and the height, width and total length of the apparatus. Brazed turning instruments are usually specified consistent with the ISO application system. Tools applied for turning cast iron and non-ferrous items are shown red. Instruments supplied for ISO application group 'M' are dyed yellow. Those used for cutting ferritic steels are dyed blue. The price of a brazed instrument is nearly one fifth of that of an indexable insertion holder. A brazed device can be reground 20 to 30 times.

The most valuable aspect is the selection of cutting objects in brazed instruments and is presented as indexable insertions. With brazed implements the selection is limited to the limit of uncoated hard metals offered. Grinding of brazed hard metal instruments is normally completed manually. The typical procedure is to apply soft, green grit silicon carbide wheels. Diamond wheels are perfect, nevertheless are greatly further costly and are not a widespread selection.

4.2 Drilling tools

As with turning apparatus, there are three groups along these lines (Figure 8):
a) High speed steel devices
b) Brazed and solid hard metal devices
c) Indexable tip tool holders.

Fig 8. Some types of drill bits

Round, ground high speed steel tool tips are directed by clamping into holes conveniently located on the end of boring bars. Square section tool tips can be utilized in the same way, however, are in much less demand.

Butt welded boring instruments are furthermore utilized for boring and are involved in the British standard BS 1296. Two boring implements are listed in this standard, with reference number 50. One tool has a square nose, meaning that the tool can bore and face, another has a round nose. Four desired sizes are indicated.

Brazed hard metal boring tools are presented in agreement with the former British Hard Metal Alliance production standard. As with high-speed steel instrument bits, the most widespread types have round rods and are fastened into drill rods in the same manner as high-speed steel tool bits [1]. Dimensions are given in imperial sizes. The two lesser diameters in the criterion, 3116" and 1;4", are made of solid hard metal.

4.3 Turning tools

Turning apparatuses can be allocated into high-speed steel utensils, brazed hard metal tools and tool holders carrying indexable inserts.

High-speed-steel turning instruments are presented in trio ways. These are high-speed-steel inserts for small utensils or, furthermore, welded tools with heads made of high-speed steel and welded to a middle carbon steel shaft. Butt-welded instruments are in the middle dimension scope. The tierce probability involves very substantial instruments where the tip of the instrument is a part of high-speed steel brazed to a steel shaft [1], [4]. Solid high speed steel tool inserts are based on ISO 5421. These ground instrument inserts involve three cross-sectional forms: round, square and rectangular.

Eight diameters reaching from 4 to 20 mm and five lengths ranging from 63 mm to 200 mm are specified for round tool inserts. These instrument inserts are best for utilize on miniature lathes and can be undoubtedly ground to cutting shapes to match most turning treatments.

Stellite turning tools are accessible as tool inserts with cutting profiles and as tipped tools. Tool inserts are solid stellite and poured instruments are generated from cast stellite inserts that are brazed to steel shafts. Nevertheless 90% of all turning instruments operating currently are of the fastened indexable insertion category. ISO 5608 is an illustration method for 'Turning and Copying Tool Holders and Cartridges for Indexable Inserts'. This is a numeral symbol arrangement like that used for the indexable insertions themselves.

5. Tool wear

5.1 Tool failure and tool wear

The combination of high tool-chip interface temperature and high pressure leads to tool failure by one of the subsequent:

(i) microchipping
(ii) gross fracture
(iii) plastic deformation
(iv) progressive wear

Microchipping refers to the separation of small pieces as small as 0.3 mm from various points on the cutting edge. When the size of the broken pieces is between 0.3 and 1.0 mm, the tool failure mode is called gross fracture. Both failure modes occur when the tool is subjected to very high cutting forces or when the machining is accompanied by the creation of a very large, developed edge. The probability of these failure modes increases when the tool material is extremely brittle. These failure modes can be largely thwarted by appropriate selection of machining parameters, tool substantial and geometry.

Tool failure by plastic deformation happens when the cutting temperature is very extreme relative to the softening point of the tool objects. This is most observed during machining with cemented carbide tools at very high cutting speeds. Consequently, of permanent deformation, the tool wedge becomes curved, resulting in a part of the tool face contiguous to the cutting edge being lowered by h1 and a part of the tool flank face alongside the cutting edge being projected by h2. The lowering of the tool face creates a substantial negative rake angle near the cutting edge, resulting in very high cutting forces. The bulging of the flank surface creates a zero or negative clearance angle, causing the tool flank to wear rapidly. This failure mode, like microchipping and large fracture, is primarily the consequence of poor machining practices and can be largely barred by appropriate choice of tool items and cutting speed [2].

If cutting is performed with appropriate assortment of tool material, tool geometry and machining strictures, the cutting ability of the tool should deteriorate gradually by wear, and the tool should be considered to have failed when the cumulative wear reaches a certain predefined level known as the wear criterion. Tool wear is mainly of two types:

(i) Type-1 wear, which occurs only on the tool flank

(ii) Type-2 wear, which occurs simultaneously on both the tool flank and the face

A third type of wear, which occurs only on the tool flank, occurs when incorrect selection of machining parameters during machining with HSS tools results in heat generation exceeding the thermal resistance of the tool material. This style of wear is an indication of poor machining practice and should not be allowed.

The type of wear a cutting tool will experience depends principally upon the type of production material, the undeformed chip depth (feed) and the cutting speed.

5.2 Growth of tool wear

The growth of tool wear with cutting time is represented by wear curves. A typical wear curve when the wear on the tool line and rake surfaces is equal. This curve consists of three distinct zones: Zone I (OA) is the initial wear zone, where the surface asperities of the link surfaces of the tool and the workpiece rub hard against each other. This zone represents the running-in period of the cutting tool and is characterized by a high wear rate. As the contact surfaces improve, the wear rate decreases, and a gradual period of uniform wear begins. This is represented by zone II (AB). When the total wear reaches a certain level, there is a sharp increase in wear, especially on the tool flank. Therefore, zone III (BC) represents the accelerated wear zone. Cutting must be stopped immediately with the onset of accelerated wear; otherwise, catastrophic failure of the entire cutting edge may occur. If the machine parameters are correctly selected, zone II accounts for about 85-90% of the tool life. As the cutting velocity expands, the length of zone II decreases. At extremely high cutting speeds, zone II may disappear completely and catastrophic failure of the tool may occur soon after the running-in period [2].

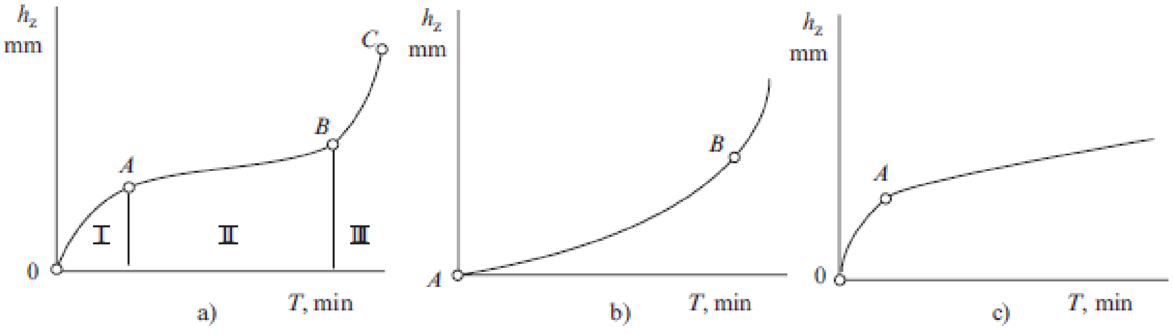

Figure 9. Alteration of tool wear with cutting time (a) when wear occurs equally on tool flank and rake face, (b) when wear on tool flank is significantly higher than at the rake face, and (c) when wear occurs only on the tool flank [2]

When the wear on the tool face is much less than that on the tool flank, the wear curve appears as shown in Figure 9(b). In this case, there is no running-in period region. In the progressive uniform wear region, wear initially proceeds slowly but accelerates as cutting time increases. The wear rate increases continuously until the tool fails catastrophically at point B.

Tool wear can also be assessed by volumetric measurements. The loss in weight of the cutting tool serves as a measure of wear. This method has been found useful in determining the wear of grinding wheels but has not been preferred in the case of cutting tools because of the difficulty of distinguishing between the contribution of flange and crater wear to the total volumetric wear.

5.3 Tool life and machinability

Tool life refers to the practical life of a tool and is the time during which a tool cuts satisfactorily or the time between two successive regrinds. Tool life can be expressed in various ways, such as:

(i) actual working time, i.e. the time during which the tool interacts with the workpiece and converts the work material into chips
(ii) total working time, with idle time, as in intermittent cutting operations such as shaping, milling, etc.
(iii) volume of material removed
(iv) number of workpieces machined
(v) total length of work machined

In machining practice, actual working time is a commonly used measure of tool life. A tool is considered to have failed when it cannot prolonged perform its designated task satisfactorily. Therefore, the failure principle depends on the conditions associated with the element being machined. For example, in a roughing procedure, surface finish and dimensional precision will be of little significance; therefore, tool failure can be attributed to the onset of accelerated tool wear or a sudden increase in cutting force. On the other hand, in a finishing operation, surface quality and dimensional precision will be the primary concern and therefore tool failure will depend on the failure to provide the desired surface quality or accuracy even if the tool wear and cutting force are within safe limits [2].

Among the wear criteria, the flange wear area width hz is the most widely used in machining practice for various reasons. Its greatest virtue is that it can be easily measured with a Brinell microscope. An additional advantage is that hz is related to the performance parameters of the cutting procedure, for example surface quality and cutting force. However, the greatest shortcoming of using hz as a wear criterion is that it is not uniform along the length and for convenience, the maximum value of hz is taken as the flank wear measure. The hz value chosen as the wear criterion depends on various factors such as the desired dimensional accuracy and surface quality, the maximum allowable cutting force and the cost of tool re-sharpening. Obviously, a small hz value will be adopted as the wear criterion for finishing cuts where dimensional accuracy and surface quality are critical, but a larger hz value will be appropriate for rough cuts to achieve economic benefits such as longer tool life.

Surface quality can be used as a wear criterion. For this, the surface quality of the machined components must be measured continuously, so that the tool can be stopped as soon as the surface roughness exceeds a certain predetermined limit. Such measurements require portable surface analyzers and several repeated observations to account for the scatter in the readings. Given these difficulties, even in finishing processes, the process criterion is related to hz and a suitably small value is adopted as the wear criterion.

When the limiting force is used as a wear criterion, a dynamometer connected to a recording device is preferably required. Since the tool/workpiece is mounted on the dynamometer and not directly on the carriage/slide/table, this reduces the stiffness of the machining arrangement. The limiting force criterion is therefore mainly used in laboratory conditions for research studies. In real shop floor machining practice, the appropriate hz value corresponding to the limiting force is determined and used as the wear criterion.

5.4 Effect of various factors on tool life

5.4.1 Effect of work material

The effect of the work substance on tool life depends largely on its physical and mechanical properties, since they determine the amount of heat spawned in the cutting procedure and its distribution between the tool, chip and workpiece. This effect can be directly attributed to the work material's machinability; the better the work material's machinability, the higher the tool lifetime, while other parameters remain the same.

Within a given group of materials, machinability can be significantly affected by chemical composition. For example, in structural steels, reducing the percentage of carbon content and alloying elements (Cr, Mn, etc.) increases machinability. In addition, steels with a ferritic microstructure have better machinability than those with a pearlitic microstructure. The adding of trivial quantities of sulfur (up to 0.1%), lead (0.2-0.25%) and phosphorus (up to 0.15%) increases the machinability of the steel without any noticeable effect on its mechanical properties [2].

Heat resistant steels have very poor machinability due to their high ultimate strength, which they can maintain without any noticeable loss up to 800°C. This outcome in a prominent amount of heat being created during cutting. The problem is further compounded by the fact that these alloys have poor thermal conductivity; therefore, the heat generated is concentrated in a narrow area close to the cutting edge, indicating intense tool wear and poor tool life.

Non-ferrous alloys, especially Al alloys, have very good machinability due to the combination of low ultimate strength, tendency to soften with increasing temperature, and high thermal conductivity. It is therefore not surprising that for a given tool life (e.g. 60 minutes), Al alloys can be machined at cutting speeds 4-6 times higher than structural steels.

Grey cast iron has relatively poor machinability compared to structural steel due to its lower thermal conductivity, higher contact pressure due to intermittent chip formation, and greater abrasive action of hard components (cementite, ledeburite). The machinability of SG iron and malleable iron is better than that of gray cast iron due to their higher ductility and the formation of arc chips during machining.

5.4.2 Effect of tool material

Cutting tool wear and subsequent tool life varies primarily on the assets of the tool substance. Among the mechanical possessions that control the performance of a tool material, the most important are high hardness, strength, toughness and wear resistance, and the competence to uphold these possessions at the temperatures prevailing throughout cutting. Tool wear is significantly affected by the thermal conduction of the tool objects. An object with high thermal conductivity will be less prone to cracking during fabrication and regrinding [2], [3].

Materials that meet the above requirements and find application in industry are high carbon and alloy steels, high speed steels, cemented carbides, ceramics and hard materials such as diamond and cubic boron nitride (CBN).

Given the fact that cutting temperatures can be quite high, the loss of hardness with increasing temperature is often the factor that limits the use of a tool material for a particular application. A tool loses its cutting ability when its hardness falls below a certain level. The highest temperature at which the cutting tool retains its cutting ability is called the critical temperature and is a critical constraint in defining the execution of tool materials. High hardness provides good wear resistance but is associated with poor grindability and low toughness. The performance of important tool materials will be discussed briefly below.

These are high carbon steels containing 0.7-1.4% C. They are quenched at 760-820°C to increase their hardness, giving them a hardness of HRC 61-63. Their critical temperature is between 200 and 250°C, which limits their application to hand tools such as chisels, hammers, presses, etc., and cutting tools operating at low cutting speeds such as taps, tapping dies, and reamers. Complex cutting tools such as drills, end mills, and form tools are also sometimes made from these steels for machining wood and soft nonferrous substances, for example magnesium, brass, and aluminum.

In addition to their high carbon content, alloy steels contain small percentages of Cr, Mn, W, and Si, which help to significantly increase their wear resistance. Some of the alloy tool steels used for metal cutting are T90Mn1Cr1W1, T90Si1Cr1, T90Cr6W1, T90Cr1W5. These steels are quenched at 820–875°C and then tempered at 150–180°C. This process produces small amounts of complex carbides alloying quantities furthermore to martensite, resulting in a hardness of HRC = 63–67. The critical temperature of these steels is in the range of 250–300°C, which allows them to be used for cutting at speeds 20–40% higher than those possible with high carbon steels. These tools are mostly used for cutting tools operating at low cutting speeds, such as drills, taps, reamers, etc. Although their application areas are like high carbon steels, their productivity is much higher.

High speed steels are ultimately high carbon steels to which carbide-forming alloying rudiments such as W, Mo, Cr, Co and V are added in larger percentages. The complex carbides formed in large quantities by these alloying elements are stable to much higher temperatures than those in carbon and alloy steels, which raise cutting temperatures to 600°C and above, thus allowing a significant increase in cutting speed. This explains the "high" speed label attached to them.

A new category of cobalt-based casting alloys was developed around 1915. These alloys contain four main elements: Co, Cr, W and C. Chromium is the main alloying element, constituting 25-35% of the carbide in the tool. Tungsten varies from 12% to 25% and contributes to the overall hardness. Carbon content varies from 1% to 3% **-** lower carbon percentages give a relatively soft and ductile tool, while higher carbon percentages give a harder and more wear-resistant tool.

These materials are not heat-treatable and are used as castings, so they are known as casting alloys. They have a critical temperature of around 750°C, a minimal constant of friction, tremendous corrosion resistance and great resistance to shock and impact. They are less hard than HSS but more resistant to wear. In general, they have properties intermediate between HSS and metal carbides and operate at cutting speeds higher than those of HSS but lower than those of carbides. They are utilized in machining cast alloys, cast iron, compliant iron, alloy steels, stainless steels, nonferrous metals, bronze, Inconel, Monel, graphite and plastics.

After high-speed steels and cast alloys, the next breakthrough in cutting tool machinery was the advancement of metal carbides in the third decade of the last century. Previously, tool objects were greatly produced by molten metallurgy and relied on suitable heat treatment for hardness and former possessions. Therefore, their hardness was affected by the cutting temperature and was limited by the hardness of available cutting tools. Metal carbides are produced by powder metallurgy and can therefore have much higher hardness and temperature resistance. The hardness in the range of HRA 87–92 and the critical temperature in the range of 800–900°C allow iron carbides to be machined at much senior cutting paces than HSS. With the development of diamond grinding wheels and non-traditional machining methods in the last few decades, metal carbide tools have become easier and cheaper to manufacture. Therefore, they are gradually replacing HSS tools in all cutting applications.

Metal carbides are carbides made of three high-temperature materials, W, Ti and Ta, sintered with cobalt binder. The hardness of a particular carbide class depends on the carbide percentage, the higher the carbide percentage, the greater the hardness. Among different carbide classes, the hardness is determined by the relative percentage of WC, TiC and TaC in a particular class. The microhardness of TiC, WC and TaC is 3200, 2500 and 1800 kg/mm2, respectively. Therefore, a given percentage of TiC will contribute more to the hardness of cemented carbide than the same percentage of WC and TaC. Cobalt is much softer in comparison. Increasing the Co content in metal carbide reduces its hardness and temperature resistance but increases its strength.

6. Conclusions

Cutting tool selection directly affects the success and economic efficiency of the manufacturing process. High speed steels, stellites, hard metals and cermets, each with different advantages and areas of use, offer important solutions for machining. With the advances in manufacturing technologies, the properties of these materials are being further improved, and productivity is being increased even more thanks to new coatings and hybrid materials. In the future, it is expected that more durable, economical and environmentally friendly cutting tool materials will be developed.

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