Review

Deposition processes and metal cutting applications of TiN coatings

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The processing techniques and metal working applications of titanium nitride (TiN) coatings are reviewed. The principal processing techniques are physical vapour deposition (PVD) and chemical vapour deposition (CVD). Individual processes within CVD and PVD are reviewed and the important process parameters identified. Various metal working applications of TiN-coated tools in turning, milling, drilling and other processes, are also reviewed. Finally, future trends and needs in the development and application of TiN coatings are identified and discussed.

1. Introduction

The use of coatings for improving resistance to wear, corrosion, or enhancing lubrication is an established technology in the metal working industry [1]. Significant research, development and application of coatings has been in evidence in the last two decades, primarily due to the desire for developing extended tool life. Some of the more important engineering coatings include titanium nitride (TiN), titanium carbide (TiC), hafnium nitride and carbide (HfN, HfC), titanium carbonitride (TiCN) and aluminium oxide (Al_2O_3). Of these coatings, TiN has a low coefficient of friction, high hardness, resistance to high temperature, and good adhesion to substrate [2]. The objective of this paper is to present a review of the development and application of TiN coatings. TiN coatings seem to be dominant in industry due to excellent performance in increasing material removal rates, aesthetic appeal (golden colour) and resistance to wear and corrosion.

In view of the large volume of available information, the review is restricted to the processing techniques and applications of TiN coatings. The various techniques for the deposition of TiN are discussed first. Machining applications and performances of TiN coatings are outlined and discussed next. Future trends in the development and use of coated tools and possible research issues are also identified.

2. Deposition techniques

The historical origins of deposition processes date back to 1907 when Soddy [3] observed that calcium vapour reacted with all gases except the inert gases. Langmuir [4] reported the formation of tungsten

nitride by vapour phase reaction between nitrogen and tungsten. Other works on the deposition of films prior to 1970 have been reported amongst others by Herrick and Tevebaugh [5], Ritter [6], and Rairden [7]. We will restrict our review to work published since 1970.

Various surface treatment processes, such as nitriding, electroplating, chemical vapour deposition (CVD) and physical vapour deposition (PVD), are available for depositing coatings onto components [1]. We will restrict our review to PVD and CVD techniques because of their very widespread use in industry.

CVD is a high-temperature coating process (approximate coating temperature 950 °C or above) that has been historically used for coating ceramics. Gases, also termed precursors, and chosen on the basis of the desired coating, are introduced into the chamber. The gases dissociate at the high operating temperatures and molecules of new compounds are deposited on the substrate. Coating is often done in an inert atmosphere to preclude its oxidation. Also, gases resulting from the coating process require additional scrubbing before release to the environment.

In direct contrast to the limitations of the CVD techniques, the PVD process requires a relatively low coating temperature (approximately 500 °C or less). The primary PVD processes are evaporation, sputtering, and ion-plating. Variants of these processes exist and will be discussed later. In evaporation, the material to be deposited is melted by resistive heating or by the heating action of high-current electron in vacuum. The vapour cloud thus formed condenses on the substrate. Coating by sputtering is

achieved by bombarding the surface of a target coating material with incident ions. This results in the stripping of target atoms from the source and deposition on the substrate. The ion plating process utilizes the high incident energy of ionized arriving target material to cause intermixing with the substrate in a vacuum. A negative voltage is applied to the substrate causing acceleration of the target ions.

3. PVD processes
3.1. Evaporation processes
The evaporation process, discussed briefly above, uses a thermal/electron beam for evaporation of target material. The condensation of the vapour on the substrate produces the thin film. Atoms in the vapour phase have very low energy (0.2–0.6 eV) and, as a result, do not produce highly adherent or dense films [8]. Fig. 1 shows a schematic representation of the basic evaporation process. This type of evaporation process suffers from two drawbacks [9]. First, non-stoichiometric films can result due to partial dissociation of compounds. Second, for high melting point compounds, such as ceramics, a high power density source is required to obtain appreciable and economical evaporation rates, leading to operational problems with the source for extended run periods.

To circumvent these problems, researchers [9] have devised the activated reactive evaporation (ARE) process for the high-rate deposition of thin films. Fig. 2 shows a schematic representation of the procedure. An electron beam provides the heat necessary to melt and evaporate the target and the electrons necessary to activate the reactions for film deposition. A probe biased to a positive or a.c. potential draws the electrons from the plasma above the molten pool into the
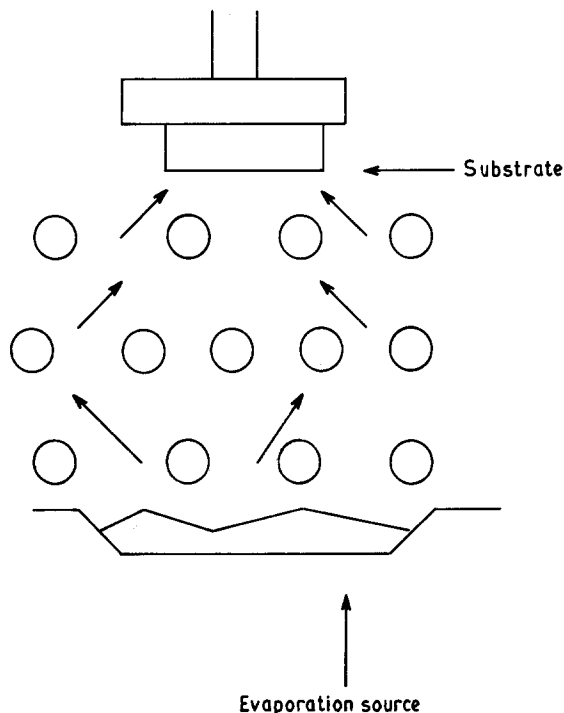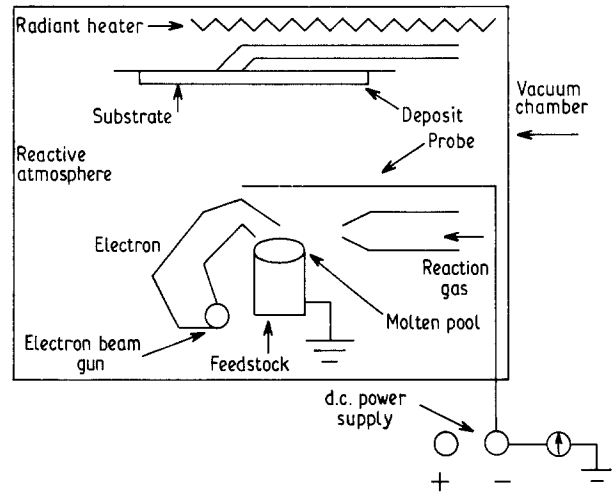

Figure 2 Activated reactive evaporation, schematic illustration (adapted from Bunshah and Raghuram [9]).

reaction zone between the pool and substrate. Reaction yield is increased due to activation of metal vapour and reactive gas bled into the system. The substrate is heated to the deposition temperature by a radiant heater. The entire system operates in vacuum. It should be noted that the main difference between evaporation and ARE is the presence of a plasma in the latter process. Modifications of the ARE process include [10] the enhanced ARE process, low-pressure plasma deposition (LPPD) process, the biased activated reactive evaporation process (BARE) and the hollow cathode electron beam gun process. Schematic illustrations of these modified processes are shown in Fig. 3. In the enhanced ARE process, a thermonic electron emitter, such as a tungsten filament, is placed between the molten pool and substrate for the deposition of refractory compounds at lower deposition rates through sustained discharge. In LPPD, the substrate is biased at a positive potential. A hot hollow cathode or cold cathode discharge electron beam is used instead of thermonic emitters for an abundant supply of low-energy electrons [11]. Various types of compounds have been synthesized by the ARE and the modified ARE processes. These include oxides, carbides, and nitrides of aluminium, titanium, tantalum, zirconium and others [10].

3.2. Sputtering
Sputtering is a widely used technique for the deposition of thin films. Fig. 4 shows a schematic illustration of the process. Ions of the target are liberated by bombardment of inert gas ions and attracted to the workpiece. Thus to deposit titanium, a titanium target would be bombarded and the resulting titanium ions deposited on a substrate in a vacuum chamber. However, this type of sputtering process is relatively slow; thus the substrate is negatively biased or magnets are added to increase the velocity and yield of ions, resulting in a better yield.

Various modifications of the sputtering process are in use. In magnetron sputtering (MS), magnets are used to confine a small target area for material removal. A large substrate area can be thus deposited

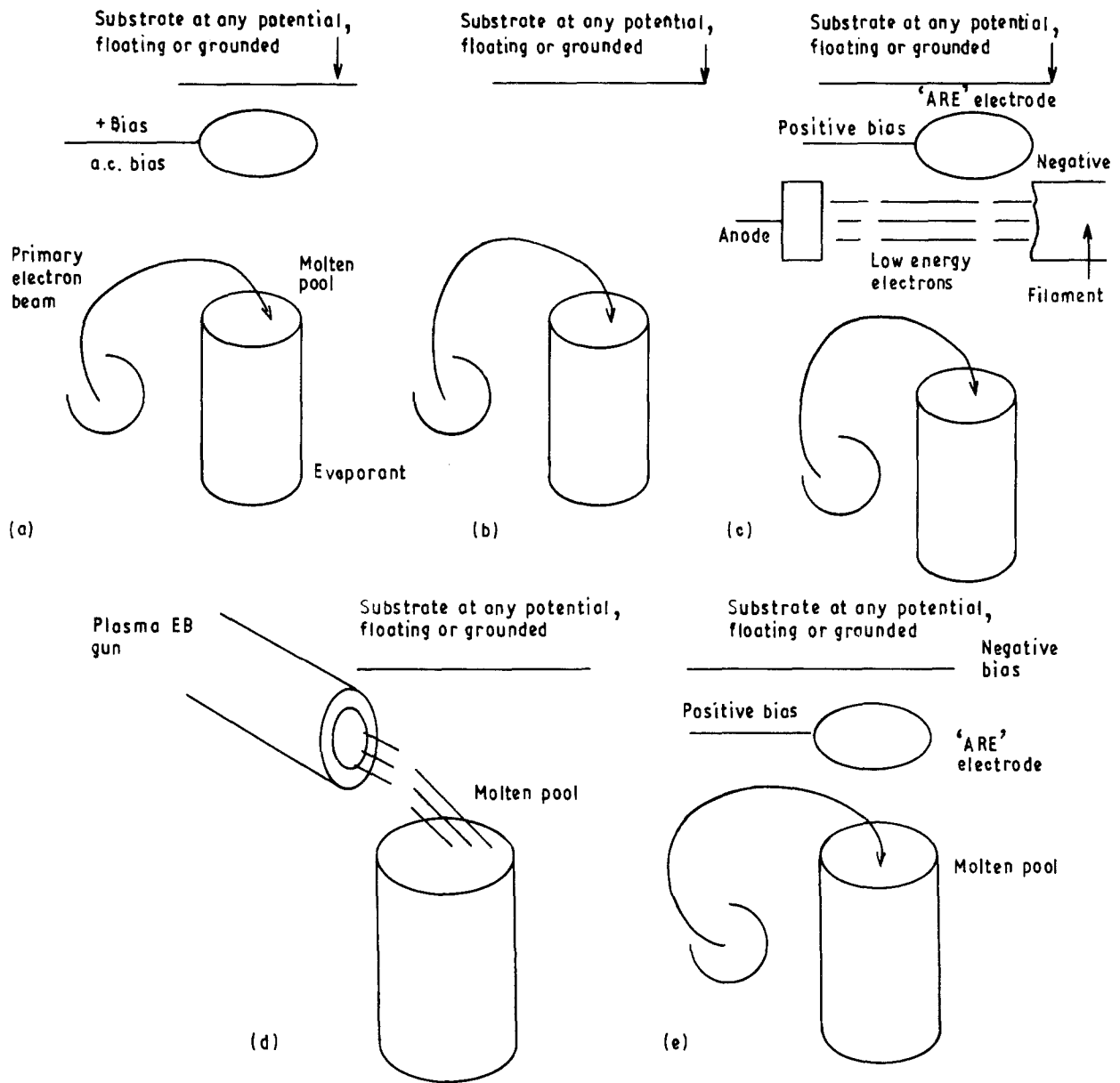Figure 1 Thermal/electron beam evaporation (adapted from Johnson [8]).

Figure 3 (a) The basic ARE process, and later variations: (b) LPPD process; (c) enhanced ARE process; (d) ARE process using a hot hollow cathode EB gun or a cold cathode discharge EB gun; (e) BARE or RIP process (adapted from Bunshah [11]).

and the deposition rate is also quicker [12–14]. Fig. 5 shows a widely used MS system. The target material is bonded at the cathode positions and substrates are loaded on pallets. The pallets are introduced into a vacuum chamber through the loadlock elevator. The reactive gases introduced through valves, are monitored by meters. The shutter opens after the deposition temperature is reached. A double cathode
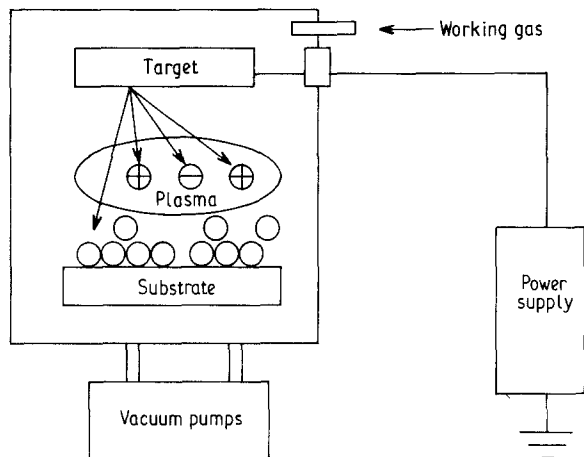

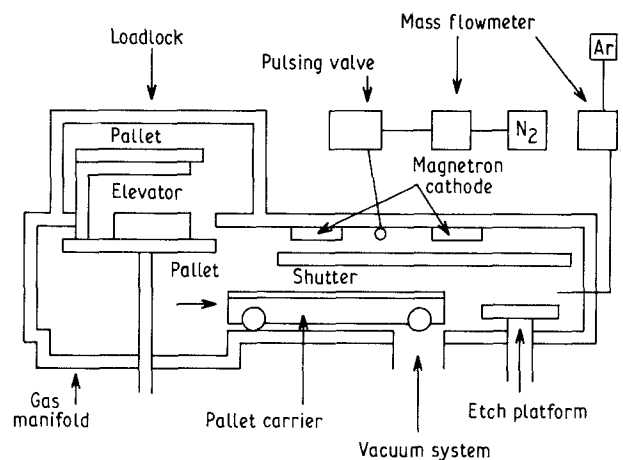Figure 4 Basic sputtering process (adapted from Flood [19]).

Figure 5 A typical magnetron sputtering system (adapted from Aronson et al. [12]).
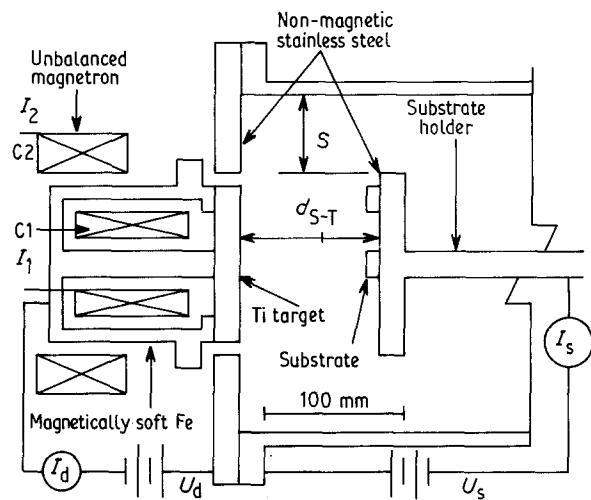
Figure 6 Schematic arrangement of the unbalanced magnetron and the sputtering system used for measurements of discharge characteristics and in deposition of TiN films (adapted from Kadlec *et al.* [16]).

configuration, in which the part to be coated is positioned between two cathodes, may also be used and this provides a uniform coating distribution on the substrate [15]. The process is also quicker because of a high ion current resulting from the double cathode configuration.

In conventional MS, there is a strong decrease of substrate ion current with increasing distance between the magnetron target and substrate [16]. This affects film properties by altering growth conditions. To increase the substrate ion current density, a magnetic confinement of the plasma by an unbalanced magnetron [16] can be used. Fig. 6 shows such an arrangement. The titanium target is mounted on a circular planar magnetron. The unbalanced magnetron consists of a conventional magnetron (C_1) and external magnetic coil (C_2). The currents produced in C_1 and C_2 are I_1 and I_2 and I_d is the discharge current. The substrate is located at a distance d_{S-T} from the target and S from the wall and carries a current I_s. It has been shown [16, 17] that by using strong external magnetic fields ($I_2 \geqslant 3$ A) the plasma can be completely confined between the magnetron target and the substrates, while the discharge can be sustained on both the target and substrate sites. This has beneficial effects on the properties of the coatings and will be discussed later. Substrates can be biased in MS and the process operates in vacuum. Enhanced energy of the ionized target material by ion-beam irradiation with Krypton [18] or various magnetron configurations [14] also yield better quality films.

To overcome slow sputtering rates a very high rate reactive sputtering process has been developed [64, 81]. Both d.c. and r.f. magnetron devices with substrate biasing have been used to attain sputtering rates as high as 95% to 100% of pure metal rates [64]. Precise control of process parameters such as, chamber pressure and target power, is necessary for this process. The equipment used is similar to that shown in Figure 5.

3.3. Ion Plating

In the ion plating (IP) process, the target material is initially melted while the substrate is bombarded with ions before deposition to raise it to the required temperature [19]. The coating flux ion is attracted to the substrate by biasing the substrate with a negative voltage. Thus sufficient ion energy is available for good inter-mixing of coating and substrate at the interface [8, 20].

Melting of the target is often accomplished by an electron beam (EB) gun. Kobayashi and Doi [21] used IP to deposit TiN film on cemented carbide inserts. Their coating arrangement, shown in Fig. 7, used an electrode configuration to draw ions to a negatively biased substrate. Other melting devices include a hot cathode and cold cathode discharge gun. The cold cathode is water-cooled and, according to Zega *et al.* [22], is easy to make and requires only a high-voltage source but no filament transformer units.

Faster coatings free of impurities can be obtained by utilizing on-line IP systems as shown in Fig. 8 [23]. The systems consist of a loading chamber for loading and preheating substrates, a process chamber for ion-bombardment and substrate cleaning prior to depos-
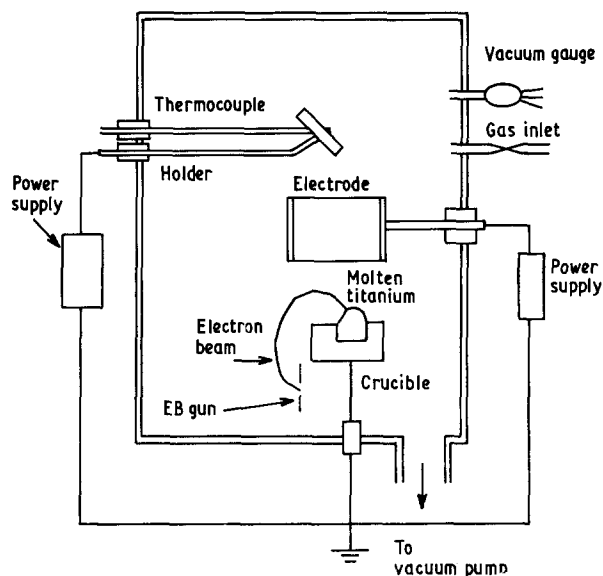

Figure 7 Schematic diagram of the ion plating system (adapted from Kobayashi and Doi [21]).
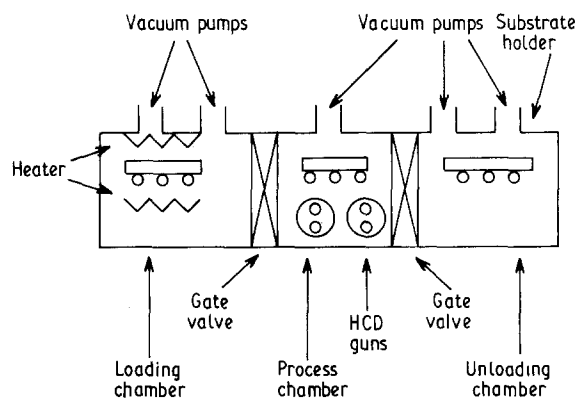

Figure 8 Schematic representation of the in-line system for ion plating TiN and TiC$_x$N$_y$ (adapted from Aoki *et al.* [23]).
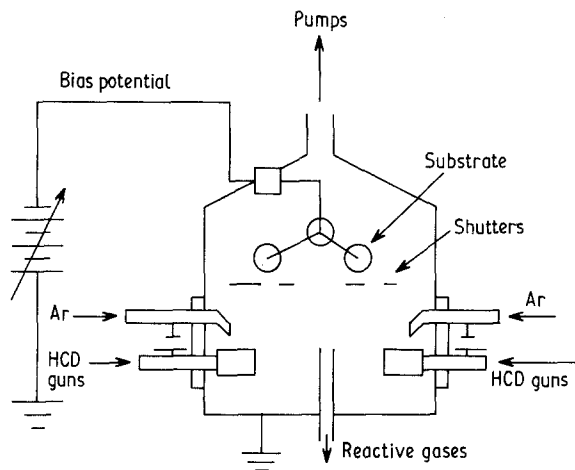
Figure 9 Schematic illustration of an ARIP System (adapted from Moll et al. [24]).

Figure 10 Schematic representation of a CAPD system (adapted from Randhawa and Johnson [25]).

ition, and an unloading chamber for substrates. Hollow cathode discharge guns are used for heating of the evaporation sources. Moll et al. [24] have combined ARE with IP to develop the activated reactive ion plating (ARIP) process. ARIP is based on arc discharges of gases where most of the electrons are generated by electron emission of the hot cathode spot. After an arc is created, it is maintained by the heat from ion-bombardment or by a heated filament. Fig. 9 shows a typical ARIP unit.

Another variation of the IP process is the cathodic arc plasma deposition (CAPD) process. Here material is evaporated by the action of vacuum arcs [25]. The source material is the cathode and arcs are sustained on it by applying voltages in the range 15–50 V, depending on the material used. An initial high-voltage pulse applied to an electrode placed near the cathode, sets the arc. This results in instantaneous evaporation of the source by random movement of the arc on the source (cathode) surface. The arc is sustained by the material plasma generated. The arc spot is typically a few micrometres in size and is subject to a high current density which causes flash evaporation of the material. Fig. 10 shows a typical CAPD unit. Unlike evaporation processes, a molten pool of metal is not created in CAPD; thus target configuration is flexible.

Electrons, ions, neutral vapour atoms, and micro-droplets are emitted from the target material. The microdroplets result in the formation of craters on targets [25]. Also, these microdroplets may be incorporated into the coatings, adversely affecting coating surface roughness [26] and can be avoided by steering the arc by a magnet. However, the cathode thickness, the gas pressure in the chamber and the strength of the current play a role in eliminating microdroplet formation. As shown by Erturk et al. [26], the microdroplet size decreases significantly thereby reducing coating surface roughness by the use of a magnetically steered arc.

Other researchers [27] have developed the reactive pulse plasma (RPP) process for the deposition of thin films. In this process, the metal vapours are obtai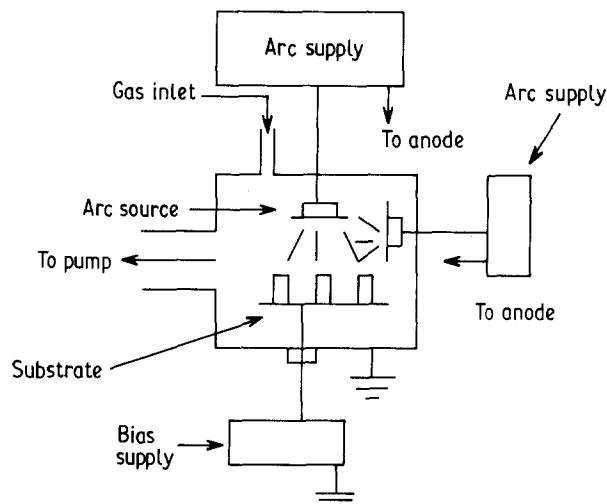ned by the electro-erosion of a hot electrode during a pulse discharge. Thus, this process is different from ARE or IP because both ARE and IP require that metal be melted by an EB gun. In RPP, the pulse plasma is generated by discharging a capacitor battery between two coaxial electrodes. The compound formed (TiN_x) is the product of the electro-erosion of the central electrode and reactive gases. Fig. 11 shows a schematic drawing of the RPP apparatus.

To summarize, the three types of PVD process for deposition of TiN films discussed are evaporation, sputtering, and ion plating. Several variants of each process exist. In essence, the processes consist of the formation of a chemical compound by the reaction of reactive gases with metal ions or vapour. The reaction or deposition rate may be enhanced by biasing the substrate. The entire process is operated in vacuum.

4. CVD processes

The CVD processes are characterized by high deposition temperatures and used for depositing TiN films on carbide or ceramic substrates. Typical process parameters for a conventional CVD process are [28]; (i) temperature (greater than 800 °C and typically up to 2000 °C); (ii) pressure (less than 1 atm and as low as
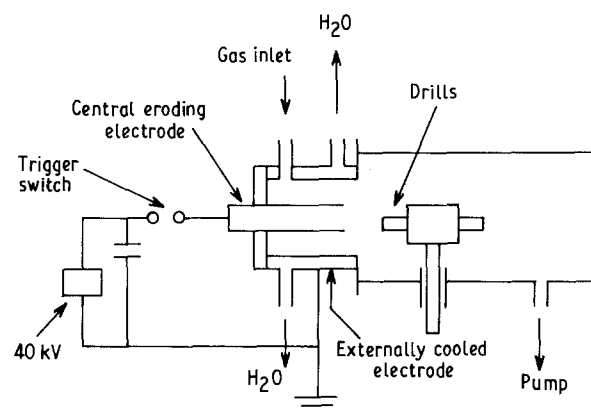

Figure 11 Schematic diagram of the RPP apparatus. (adapted from Michalski et al. [27]).

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10^{-6} torr; 1 torr $\simeq 1.3332 \times 10^{-2}$ Pa); (iii) precursors – these include reactive gases such as metal halides and carbonyls, reducing gases such as hydrogen, inert gases such as argon, nitrogen and other gases such as CH_4, CO_2, NH_3 and other hydrocarbons.

Some important aspects of the CVD process control are: (i) process variables (deposition temperature, pressure of reactive gases, and input gas composition); (ii) system chemistry (compositions of possible chemical species formed during the reaction, their thermodynamic and kinetic properties and reaction mechanisms); (iii) mass transport properties (diffusion, thermal convection and forced convection of gases); (iv) flow behaviour (type of fluid flow, flow patterns, viscosities and velocity of gases).

In CVD, a chemical reaction occurring between a titanium compound and reactive gases leads to the formation and deposition of TiN on substrates in a closed reactor. A typical reaction for the formation of TiN is [29]

$$TiCl_4 + 2H_2 + \tfrac{1}{2}N_2 \xrightarrow{(750\,°C)} TiN + 4HCl \quad (1)$$
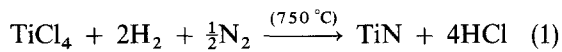
The hydrogen and nitrogen can be bubbled through liquid $TiCl_4$ before bleeding into the reactor [29]. Prior to deposition, the entire coating chamber should be purged to reduce the risk of coating contamination. It is also necessary to incorporate a scrubber unit for treating reaction off-gases. Additionally, thermocouples are mounted in very close proximity to the substrate to measure and monitor the deposition temperature. Fig. 12 shows a typical CVD apparatus.

Two main reactor types are used in CVD processes [30]. These are the hot-wall reactor and the cold-wall reactor. In the hot-wall reactor, a furnace surrounds the reactor tube and maintains the substrates and the wall at the same temperature. Although many pieces can be coated in the same run, contaminants may be introduced due to chemical reaction between reactor wall and vapour.

The cold-wall reactor, on the other hand, maintains the substrates at a higher temperature than the wall. This implies deposition only on substrates. The risk of contamination is considerably reduced here.
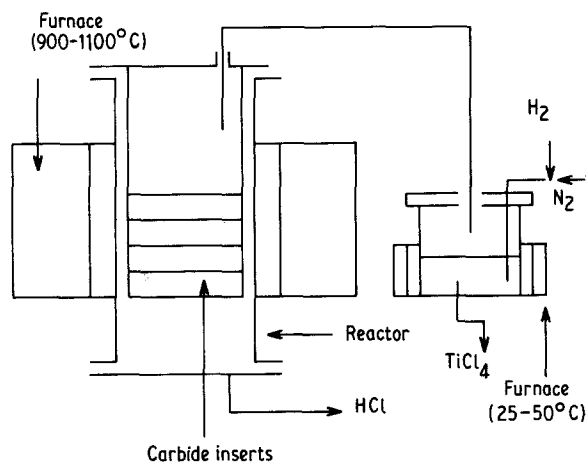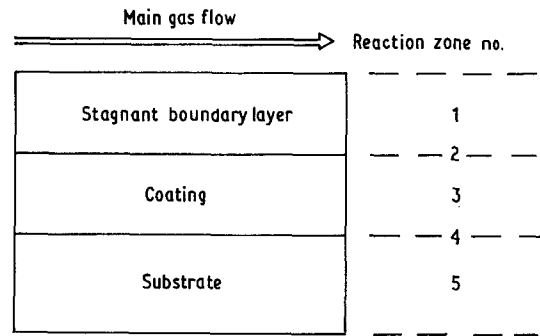

Figure 13 Important reaction zones in CVD (adapted from Carlsson [30]).

The entire reaction chamber can be divided into five reaction zones, as shown in Fig. 13 [30]. In zone 1, homogeneous reactions may occur leading to homogeneous nucleation, and consequently, non-adherent coatings. Heterogeneous reactions occur in vapour-coating phase boundary in zone 2. In zones 3–5, various solid-state reactions, such as phase changes, precipitation, recrystallization, grain growth, etc., may occur. Zone 4 is a diffusion zone; various intermediate phases may be formed here.

As mentioned before, CVD processes require high temperatures. Low-temperature CVD processes have also been developed [31]; in one process $TiCl_4$ and NH_3 react between 400 and 700 °C to produce TiN in the presence of argon, nitrogen or hydrogen as the carrier gas. The reaction, at atmospheric pressure is

$$6TiCl_4 + 8NH_3 \rightarrow 6TiN + N_2 + 24HCl \quad (2)$$

In this process, laminar flow conditions must prevail to produce good quality films.

Plasma-assisted CVD (PA CVD) is another low-temperature CVD process. Here the bombardment of the substrate with hydrogen ions raises the substrate to the coating temperature [32]. Once a stable glow is obtained, nitrogen, $TiCl_4$, and argon are introduced into the reaction chamber at fixed flow-rates. The deposition temperature is between 425 and 600 °C. Fig. 14 illustrates one type of a PA CVD reactor [28]. Laser CVD (LCVD) is a popular deposition technique in the microelectronics field [28]. The gas species are
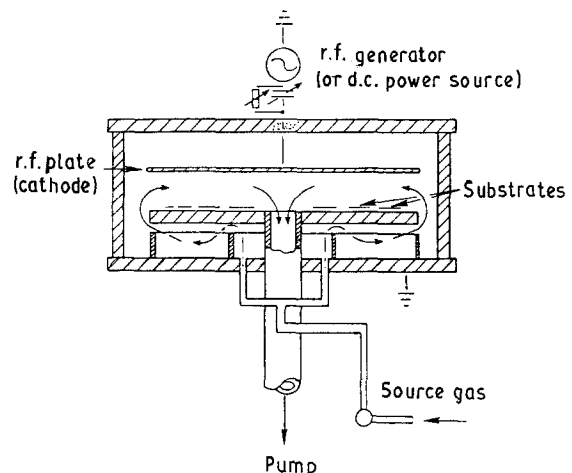

Figure 12 Schematic diagram of TiN CVD-coating apparatus (adapted from Peterson [29]).

Figure 14 Schematic illustration of a PA CVD apparatus (adapted from Bhat [28]).
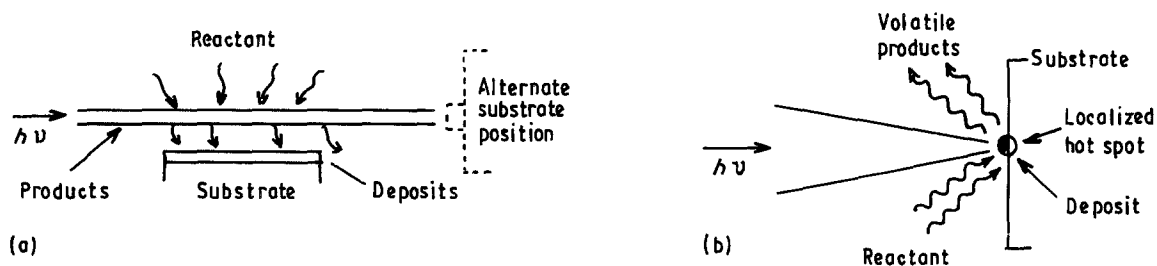
Figure 15 Schematic illustration of an LCVD apparatus (adapted from Bhat [28]). (a) photolytic LCVD, (b) pyrolytic LVCD.

activated by the introduction of a laser beam into the reactor. The LCVD process creates high-energy electrons in a very narrow energy band and localized activation of the gas volume assists in considerable lowering of the deposition temperature than conventional CVD. Fig. 15 shows a schematic arrangement of LCVD System [28].

The fluidized bed CVD technique combines fluidized bed heating and CVD [28] and is used primarily for coating of fine powders with suitable films for special applications. The coating of nuclear fuel particles to contain the fission products and the manufacture of high-purity silicon are two examples of the use of this method.

For usual CVD conditions, surface kinetics control (SKC) and mass transport control (MTC) are the two major rate-limiting steps of the process. In SKC, the deposition rate is lower than the mass input rate into the reactor while MTC of the process occurs at high pressure and temperatures [33]. The dependence of growth and the rate of a CVD film on temperature (rate-limiting steps) are illustrated in Fig. 16 [34].
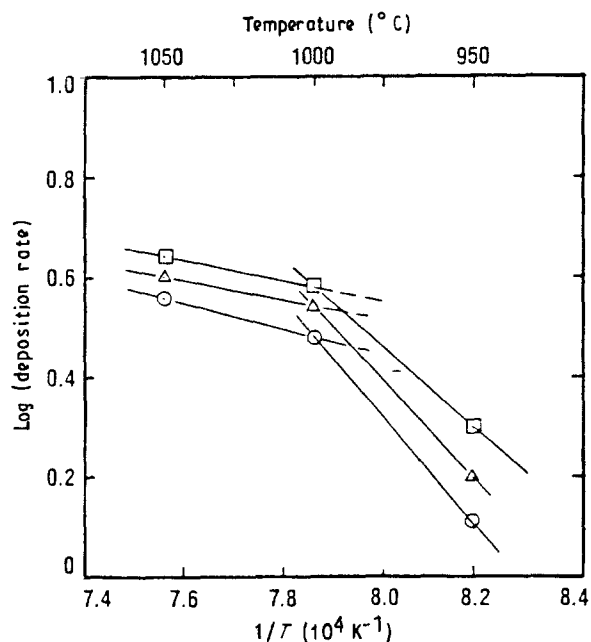

Figure 16 Growth rate and temperature characteristics of CVD; TiN process coating. $H_2/TiCl_4$: (O) 11.1, ($\triangle$) 20.0, ($\blacksquare$) 33.3 (adapted from Shah and Bhat [34]).

5. Process parameters

Table I contains a list of the major parameters governing the PVD and CVD processes. These parameters were obtained after reviewing literature relating to the processing of TiN coatings by various processes. An X indicates the relevance of a parameter to a process.

TABLE I Major parameters of CVD and PVD processes

Parameters	PVD			CVD
	ARE	IP	Sputtering	
Deposition temperature	×	×	×	×
Power to target	×	×	×	
Probe current	×			
Probe voltage	×			
Accelerating voltage		×		
Substrate current			×	
Discharge current			×	
Discharge voltage			×	
Plasma voltage				×
Gas to metal ratio (N_2/Ti)	×	×	×	
Gas to liquid ratio ($N_2/TiCl_4$)				×
Target to substrate distance	×	×	×	
Reactive gas pressure	×	×	×	×
Gas flow rate	×	×	×	×
Substrate bias	×	×	×	
Deposition rate	×	×	×	×
Deposition time	×	×	×	×

In this context, it is necessary to state the individual components of the film deposition system. The deposition chamber is usually made of stainless steel. In the ARE or IP systems, an EB gun or a cathode gun is required for the vaporization target. For sputtering systems, a magnetron is necessary for providing balanced or unbalanced MS sources. If steering of the arc is necessary, for example in CAPD devices, then provisions must be made for adequate magnetic arc steering mechanisms. As the entire deposition process is done in a high vacuum (less than 10^{-4} torr) a differential pumping arrangement is necessary. Flow control devices are necessary for control of gas flow rate and mass spectrometers may also be used for the measurement of partial pressures of reactive gases. Power sources are necessary to provide power to target, substrate heating and bias, arc power, and ion acceleration voltage. Thermocouples or other temperature measuring devices are usually used for monitoring the deposition temperature.

6. Surface preparation

Surface preparation of the substrate is extremely important for the deposition of film with superior qualities [35, 36]. It may be defined as the conditioning of the surface of the substrate before film deposition. Surface contaminants are reduced, physical, mechanical, and/or chemical properties altered, and the surface is activated to enhance reaction with the nucleation of desired film species [37]. Surface cleaning may involve removal of gross contaminants by using solvents, emulsifiers, etchants or abrasives; or the removal of particulates. Usually the best tool surface for coating is finely ground, bright, and without any black oxide layers or any other form of surface treatment [36]. Sputter etching of the substrate prior to film deposition is one widely used surface preparation process [38]. Outgassing of the chamber to establish a pure deposition atmosphere is also followed [39, 40]. Substrates may also be cleaned ultrasonically [13] or polished.

7. Metal cutting application of TiN-coated tools

TiN-coated tools are used by industries to process a variety of materials. The cutting tool material is a critical factor in the reliable manufacture of components. Despite the large range of tool materials available, there is no ideal tool material. The most commonly used tool materials are high-speed steel, tungsten carbide, cermets, ceramics and diamond. The market positions for the different cutting tool groups for machining as compiled in the year 1988 is shown in Fig. 17 [41]. In many applications the wear and heat resistance of the cutting tool materials is inadequate. The wear and heat resistance has been improved by the introduction of coatings. It has been found that by the use of coatings (a) the cutting speed and feed rate may be increased without a significant effect on tool life, (b) hard to machine alloys can be machined with greater ease. As discussed before, TiN coatings have
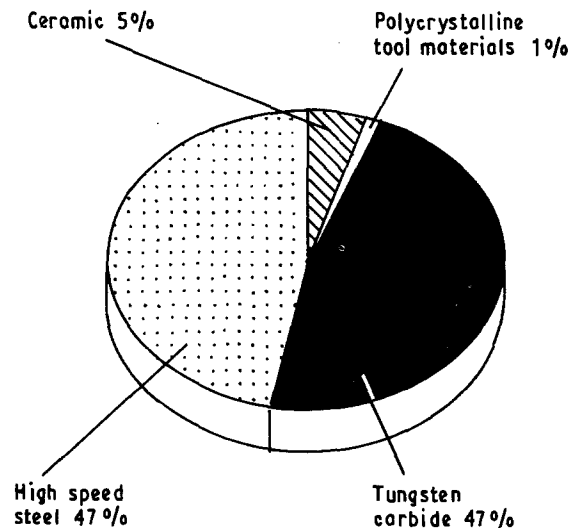
Figure 17 Cutting tool materials and their areas of application (adapted from Byrne and Bienia [41]).

high hardness, good adhesion to substrate, chemical stability, low coefficient of friction, good bonding to substrate, and very little or no porosity. These properties are ideal for its use in metal cutting applications [1, 2] because of lesser cutting forces [43] and consequently, lesser tool wear. The advantages of using CVD coated cemented carbide tools are recognized today [44, 45] and have led to the commercial applications for almost two decades [46–49].

In this section, a review of literature pertaining to the application of TiN coated tools in various areas of manufacturing is presented. The performance and wear characteristics of TiN coated tools in turning, milling, and drilling are reviewed in sequential order. Results are also presented and discussed for other metal working processes.

7.1. TiN coating performance in turning

The effectiveness of TiN CVD-coated cemented carbide inserts was reported by [50] in the turning of steel in the speed ranges between 200 and 1200 surface feet per minute (sfpm). Fig. 18 shows the improvements obtained by coating TiN over TiC-coated tools.

Wear modes of TiN-coated cutting tools in turning are found to vary with material–tool combination. Molarius et al. [51] noted cratering to be the major wear mode in turning of AISI 8620 steel by IP TiN coatings on HSS inserts with lesser flank wear. The lowest flank wear was for an insert containing 50 at % N in the TiN film and the performance of coatings containing α-Ti (33 at % N) was poor. Fig. 19 shows the wear characteristics and effect of nitrogen content on tool life. A similar dependence of cutting performance on nitrogen AISI 316 content was observed by other researchers in the turning of stainless steel by IP TiN-coated HSS inserts [52]. Fig. 20 shows the effect of nitrogen content on the cutting time. The improved wear resistance is attributed to the presence of Ti_2N phase in the TiN matrix. This phase has been reported to have high wear resistance properties [53–55]. This finding is similar to other previous work and indicates a dependence of cutting performance on
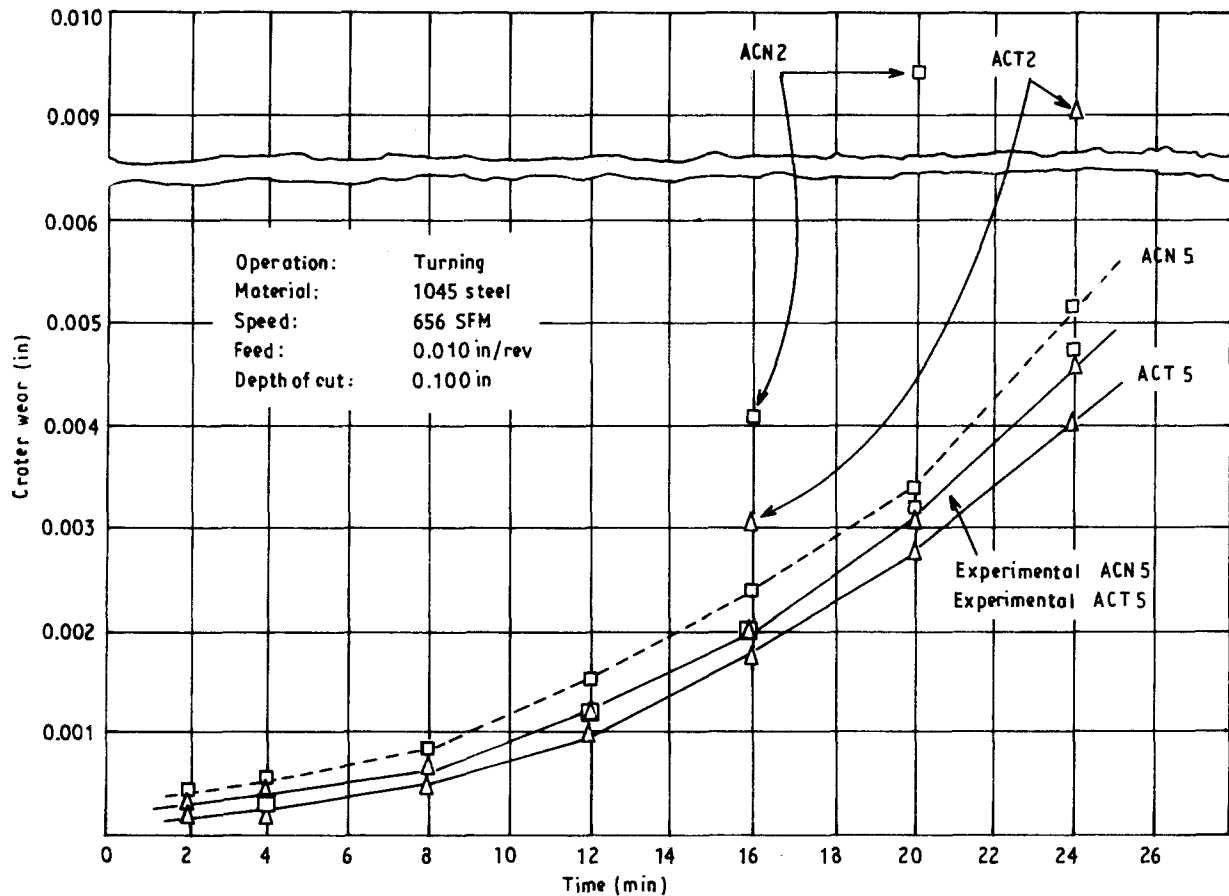
Figure 18 TiN versus TiC coated cutting tool performance. ACT, TiC coating; ACN, TiN over TiC coating (adapted from Kalish [50]).

the process type and parameters [52, 56–58]. A similar dependence has also been noted for the mechanical properties on process parameters. Additionally, coated-tool performance is heavily dependent on substrate material selection, metallurgy and heat treatment, edge finish, surface finish, end user, and tool treatment [59, 60].

Dearnley et al. [61] conducted a series of quick-stop turning tests to determine interface CVD-coated tool conditions in the machining of spheroidal and graphitic cast irons and two grades of steel. The three distinct interfacial zones observed were (a) the main chip/tool, interface, (b) the peripheral chip/tool contact at the outer edges of the chip, and (c) the flank/workpiece interface. For cast-irons, quick-stops were made at 60 m min^{-1} and above, while for the steels, quick-stops were made at 180 m min^{-1} and above. Depths of cut were set at 2.0 and 1.3 mm, respectively, and a feed-rate of 0.25 mm rev^{-1} was used. TiN; TiC; TiC, TiCN, TiN; TiC, Al_2O_3 and TiN, Al_2O_3 were the coatings used on carbide inserts.

Dearnley et al. [61] observed that the built-up edge (BUE) was almost non-existent in the machining of steel using coated tools. However, a BUE, though present in the machining of irons at speed ranges noted above, reduced significantly as the cutting speeds increased. They also observed shorter chip/tool contact lengths for coated carbides due to the lower interfacial bond strength than for uncoated ones. As chip/tool contact length determines the magnitude and position of the maximum rake face temperature,

shorter chip/tool contact lengths were attributed to lower wear in the coated tools.

As a follow-up, Dearnley et al. [62] conducted additional investigations of the wear mechanisms in the machining of iron and steels using CVD-coated carbide tools. Workpiece and tool materials used were as before. They observed that the extent of wear was work-material dependent and most coated carbides were worn more rapidly on the flank face than rake face except for TiC-coated carbides. Their experiments also showed that no coating material was universally superior to the others with respect to wear, although overall, TiN was better for rake face protection. Diffusion/dissolution of coatings into workpiece and discrete plastic deformation/fracture mechanisms were attributed to cause tool-face wear. Oxidation and fatigue cracking were stated as reasons for notch wear. The authors stressed the necessity of determining factors that govern coating adherence, particularly the presence of a diffusion layer between coating and substrate. Thus, it is believed that the parameters of the coating process should be examined in determining coating effectiveness for different materials.

In turning of AISI 1045 steel, Quinto et al. [56] observed lesser flank and crater wear for PVD-coated inserts (see Fig. 21). In these turning experiments, CVD-coated tools failed mostly by crater wear, whereas both flank and crater wear were the failure modes in PVD-coated inserts.

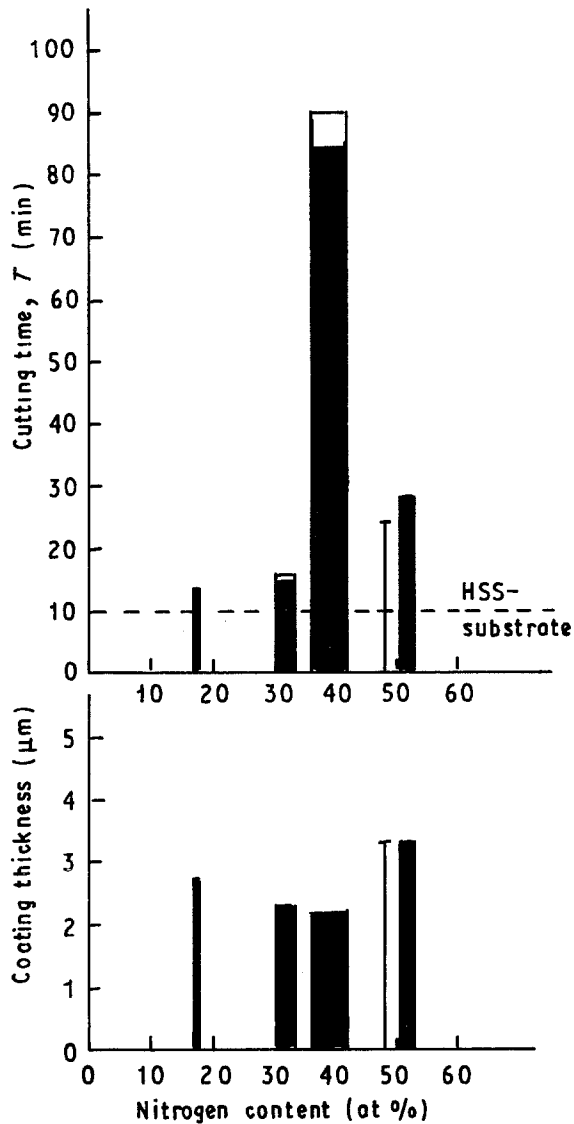Silicon nitride cutting tools have become popular in the high-speed machining of cast irons due to their

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Figure 19 Wear characteristics versus nitrogen content (adapted from Molarius *et al.* [51]).
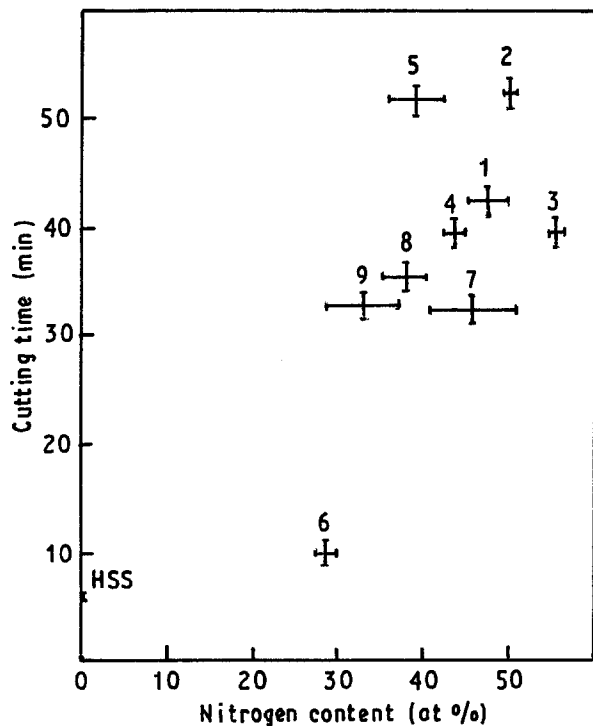

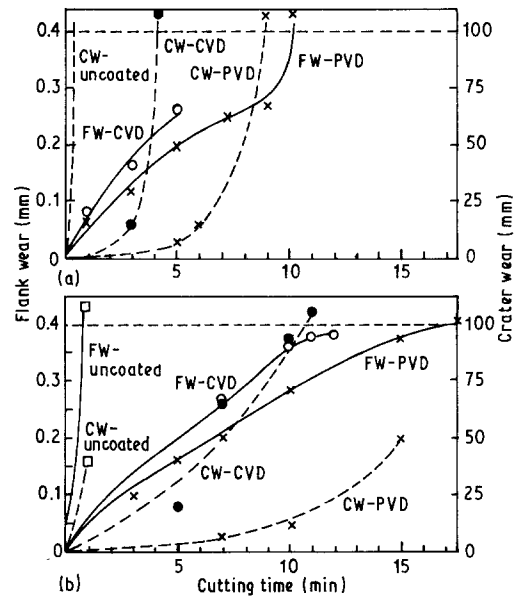*Figure 20* Effect of nitrogen content on cutting time (adapted from Molarius *et al.* [52]).

Figure 21 Flank and crater wear characteristics for coated inserts (adapted from Quinto *et al.* [56]).
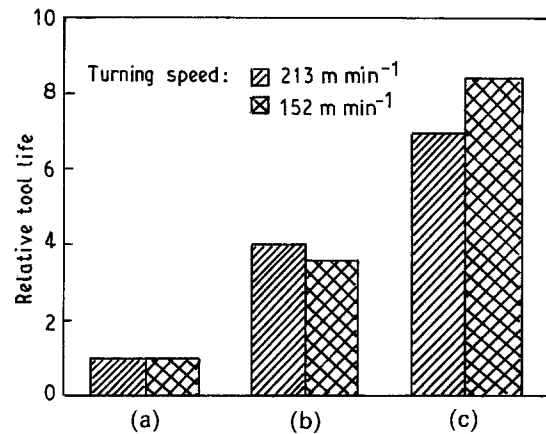

Figure 22 Tool life comparison of coated and uncoated tools, with HPSN substrate, 4340 steel workpiece. (a) uncoated, (b) TiN coated, (c) interlayer + Tin coated (adapted from Rebenne *et al.* [63]).

very good thermal stability and wear resistance. Rebenne *et al.* [63] have demonstrated that the formation of an interlayer during the CVD deposition of TiN on Si_3N_4 cutting tools was beneficial for increasing tool life in the turning of AISI 4340 steel at cutting speeds of 213 and 152 m min^{-1}. An 835% increase in tool life over uncoated tools was observed. Fig. 22 exhibits the results of their tests.

7.2. TiN coating performance in milling

A comparison of milling performance of tools coated by CVD and PVD processes has shown that the superiority of one over the other is situation specific [64]. Rich and Woerner [65] tested the performance of TiN-coated cemented carbide inserts by PVD and CVD in milling of nodular iron. Two different coating thicknesses, 2 and 5 μm, were used. The tests indicated that CVD-Coated inserts had better resistance to spalling than PVD-coated ones. Fig. 23 shows spalling data for various coatings and substrate combinations. Further, PVD coatings spalled cohesively and adhesively at the substrate without substrate
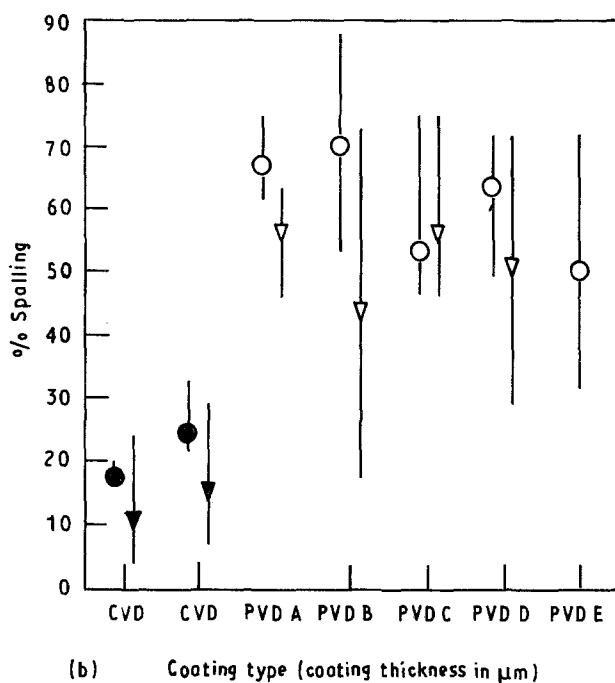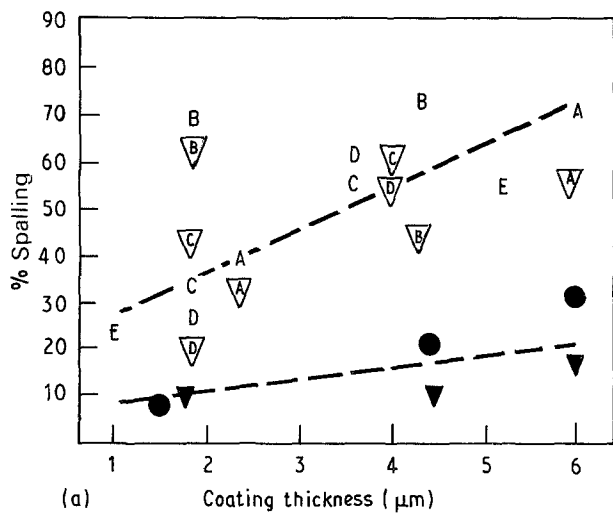
Figure 23 Spalling data for coating types. (a) CVD coating on (●) M30, (▼) P30 substrate; PVD coating on (○) M30, (▽) P30 substrate. (b) average spalling (○) M30 substrate, (▽) P30 substrate (adapted from Rich and Woerner [65]).

Figure 24 Tool-life data in milling AISI 4140 steel: (a) Alloy A: (b) Alloy B (adapted from Quinto et al. [56]).

damage. CVD coatings, on the other hand, often do not exhibit adhesive failure but during removal take substrate particles with them [66].

Quinto et al. [56] on the other hand, concluded that PVD TiN was superior to CVD TiN coating in increasing metal cutting performance of cemented carbide tools. The transverse rupture strength (TRS) and hardness of PVD-coated carbides were better than their CVD counterparts. In fly cut milling of AISI 4140 steel, Quinto et al. [56] observed lesser flank and crater wear for PVD-coated inserts (see Fig. 24). In these milling experiments, severe edge chipping was observed for CVD-coated tools. Here also, PVD-coated tools exhibited better performance. This inferior performance of CVD-coated inserts may be attributed to the increased edge chipping sensitivity at high deposition temperatures and the presence of tensile stresses in the plane of the film. Tool failure by edge embrittlement can result by depletion of carbon
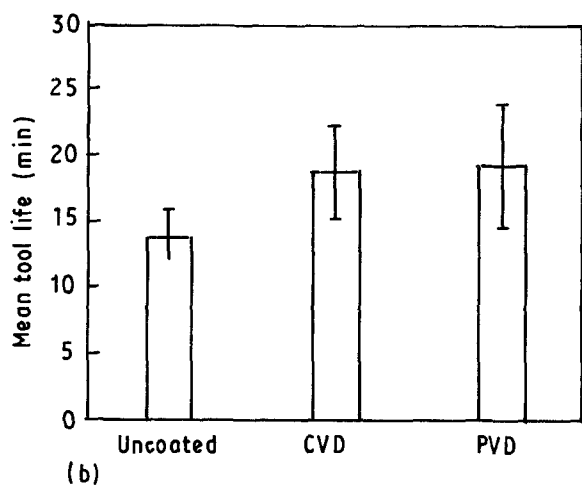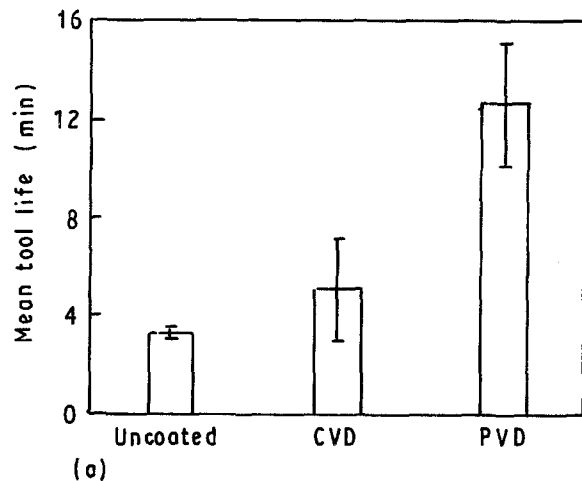
from the edge by diffusion [67]. It has also been observed that the yield stress and hardness converge to much lower values with temperature [57]. The presence of tensile residual stresses in the plane of the film is detrimental to the fracture toughness of TiN films deposited on cutting tools as they lead to thermal cracks [57]. Compressive residual stresses, however, are judged to be beneficial for metal cutting performance [56, 57]. PVD processes, generally, impart compressive stresses on the film; this may explain improved performance of PVD-coated inserts in specific situations.

Wear mechanisms in fly milling of AISI 4140 steel by CVD and PVD TiN on carbide inserts reveal the initiation, propagation and meeting of vertical cracks normal to the cutting edge and lateral cracks parallel to the cutting edge, to produce failure at both flank and crater faces [68]. CVD- and PVD-coated inserts also exhibit larger scatter of tool-life data [51, 68]. This scatter is dependent on coating process parameters and metal cutting parameters. Niemi et al. [69] observed flank wear as the main wear mode and an inverse relationship between coating hardness and wear resistance in the hobbing of case-hardened steel by PVD-coated TiN HSS hobs. This is a very surprising finding; normally better wear resistance is exhibited by harder films. Thus, simple mechanical tests, for

example, hardness and scratch tests may not be suitable indicators for film properties designed to withstand severe conditions, such as, metal cutting.

7.3. TiN coating performance in drilling

Randhawa [58] studied the effects of three PVD processes in the performance of TiN-coated HSS twist drills, end mills and taps. The cutting tools were coated by arc evaporation (AE), IP, and sputtering. The adhesion of the coatings was found to depend on the shape and size of the MC carbide phase. Higher surface roughness of the substrate produced poor coating adhesion. The tools were used to create holes on 4150 AISI/SAE steel. Coatings containing a large number of macroparticles (by the AE process) exhibited the worst tool life. However, after suitable control of these macroparticles, better tool-life was obtained. The macroparticles acted as sources of abrasive wear, resulting in coating spallation. The TiN-coated tools exhibited superior life compared to uncoated ones and this is seen in Fig. 25.

Sproul and Rothstein [70] observed a significant scatter of tool-life data among PVD-coated TiN inserts; an interesting observation was the degradation of tool life while using cutting fluid in drilling AISI 4340 steel.

In a study of drilling various grades of steel using coated HSS drilling and hobbing tools, Konig et al. [71] observed that surface preparation was extremely important for proper adherence of the coatings. By controlling the material removal rate and surface roughness of the tool surface in grinding for surface preparation and subsequent coating, flank wear was reduced considerably. The authors also observed that the characteristic of the grinding wheel had a bearing on the adherence of the coatings to the substrate. The dependence of tool-life on the thickness of the coating was another important finding of this investigation. This conclusion was based on the observation that thicker coatings remained intact longer and prevented workpiece–substrate contact, resulting in higher tool lives. Konig et al. [71] also stated that tool performance was dependent on the alloy composition of the substrate material. According to them, hardness of the substrate causes resistance to wear. However, in the context of their research, the effect of substrate composition on coating adherence has not been explicitly stated.

Valikhani and Chandrashekhar [72] conducted an experimental investigation to determine the performance characteristics of TiN- and ZrN-coated split-point drills in the machining of Inconel. The comparison of the performance characteristics was based on the measurement of the mean values and dynamic fluctuations of the cutting force and the number of holes drilled under the same machining conditions. Power spectrum plots of the drift force, axial force, and torque were obtained. Results showed that the ZrN coatings performed better than TiN coating because the mean values of the axial force, drift force, and torque were smaller. The dynamic fluctuations of forces and torques about the mean were smaller, while the number of holes drilled by ZrN-coated split-point drills were significantly larger than those for TiN-coated drills. Fig. 26 compares the performance of TiN- and ZrN-coated drills.

As a follow-up, Chandrashekhar et al. [73] conducted additional investigations into the influence of ZrN- and TiN-coated drills in the drilling of Hastelloy. The comparison of the two coatings and tool wear was based on the measurement of static and dynamic forces and torques, power spectral density, and acoustic emission plots. The magnitudes of the forces and torques for both the TiN- and ZrN-coated drills were approximately the same. However, a comparison of the power spectral density curves for the two coatings revealed a greater power content of ZrN. Also, the root-mean-square values of the acoustic emission energy were higher for ZrN-coated drills. This suggests that TiN coatings are better than ZrN in drilling Hastelloy as is seen in Fig. 27. Thus, it is likely that the effectiveness of a coating is dependent on the work material and the process.
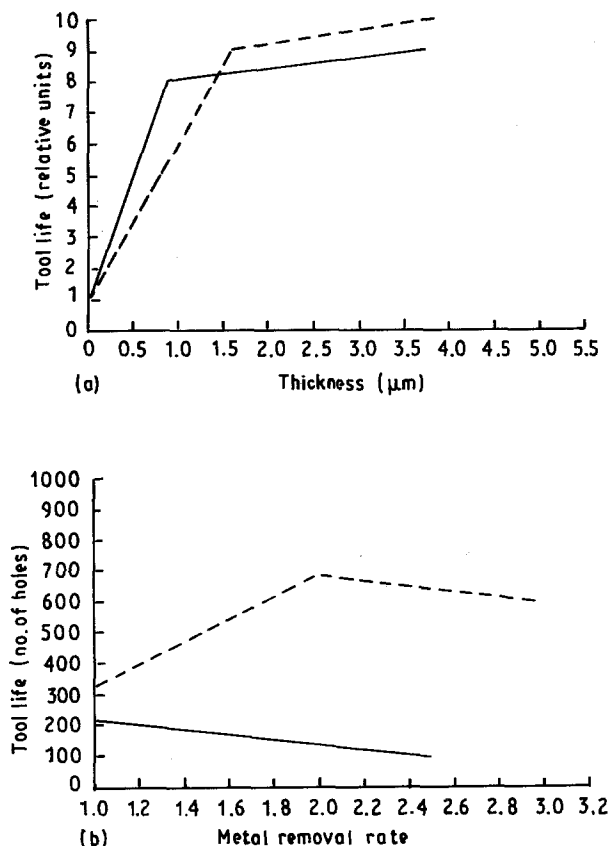

Figure 25 Tool-life dependence in drilling. (a) (——) Standard rate, (— — —) accelerated rate. (b) Jobber drills (——) uncoated, (— — —) TiN coated (adapted from Randhawa [80]).

7.4. TiN coating performance for other processes

Flood and Walsh [74] showed that improvement in the productivity and tool-life was obtained by using TiN-coated tools in a wide spectrum of operations. Results are provided for the use of reamers, gear hobs turning inserts, taps, milling cutters, broaches, and
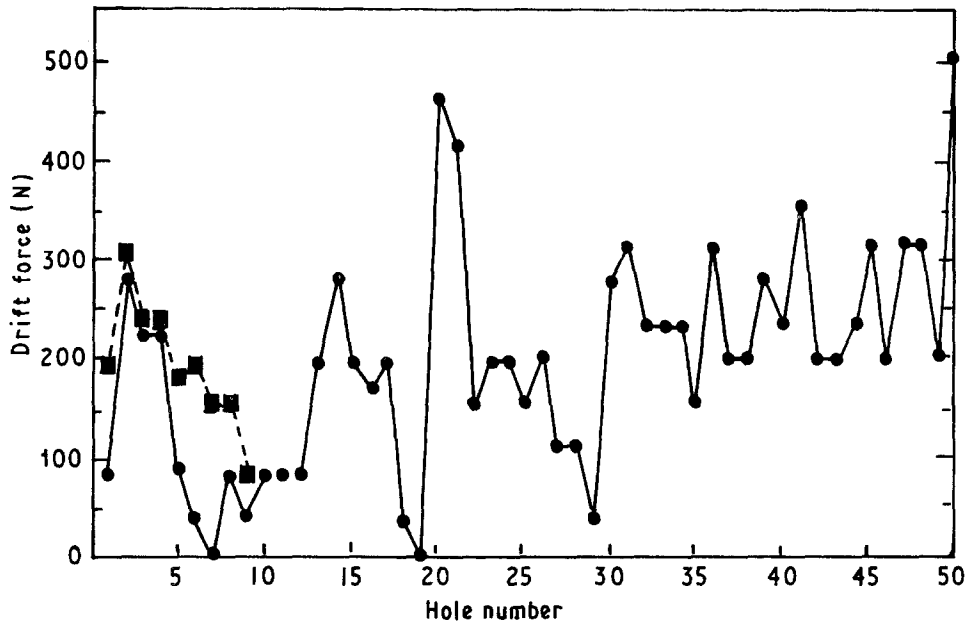
Figure 26 Comparison of (■) TiN- and (●) ZrN-coated drill performance (adapted from Valikhani and Chandrashekhar [72]).
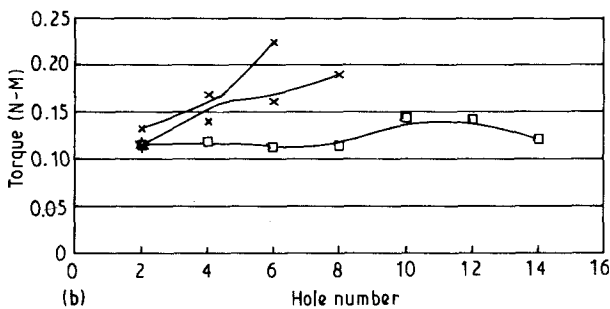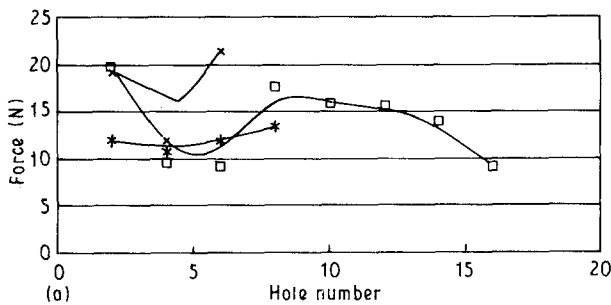

Figure 27 Comparison of TiN- and ZrN-coated drill performance in drilling Hastelloy. (a) Variation in dynamic force with hole number; (—✱—) Series 1 ZrN, (—◻—) Series 2 TiN, (—×—) Series 3 Uncoated. (b) Variation in dynamic torque with hole number. (—✱—) Series 1 ZrN, (—◻—) Series 2 TiN, (—×—) Series 3 Uncoated. (adapted from Chandrashekhar *et al.* [73]).

shaper cutters. The machining speeds and feeds ranged from 20 sfpm for broaching to 745 sfpm for turning, and 0.2 in/rev to 0.065 in/rev for turning, and 0.003 in/tooth for milling, and 0.25 in s^{-1} for broaching.

In broaching, the lower friction, cutting forces and resistance to metal adhesion of TiN coatings were observed to yield significant productivity and tool-life improvement [75].
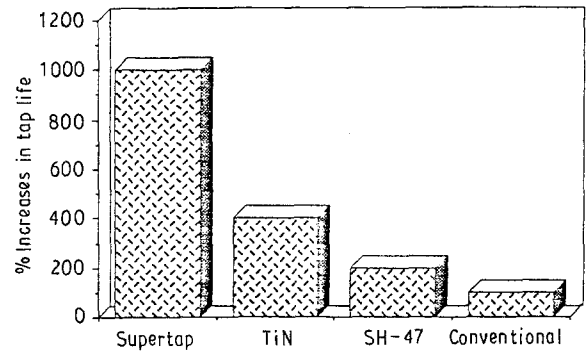

Figure 28 Comparison of tapping results between coated and uncoated taps. Supertap outlasts conventionally designed taps coated or uncoated (adapted from Miskinis [76]).

It has been shown that there exists an interactive relationship between the performance of TiN-coated taps and tap design [76]. Tapping is a very expensive and time-consuming operation, and it is important to increase the speed of operation while maintaining a useful tap life. It has been observed [76] through controlled testing of the effect TiN coats on taps, that for significant improvement of tap life, tap geometry, style and part material are important. Several alternative tap designs, cutting face geometries, and tool materials enabled the development of a tap with superior performance. The authors observed a 1000% increase in tap life when using the newly TiN-coated taps. In all the reported cases of the use of TiN-coated tools it is observed that extended tool-life, more regrinds of the cutting tool, increased cutting rates, and improved surface finish resulted. Fig. 28 shows results of performance tests of TiN-coated taps.

There is limited information on the effectiveness of TiN coatings in machining of superalloys and composite material. Harder, tougher materials pose the problems of high cutting temperatures and forces. As pointed out above, room-temperature hardness tests

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may not be sufficient to predict metal cutting properties at these conditions. Quinto et al. [56] have observed a convergence of hardness to lower values at elevated temperatures. (800–1000 °C). This may drastically effect performance of TiN coatings in machining superalloys and composites.

8. Future trends

In order to alleviate the problem of rapid tool wear, multi-layer coated tools have recently been introduced [49]. In one such multi-layer tool, TiN is the outermost layer and sandwiches other different layers [77]. Each layer of the multi-layer coated tools performs a specific function. For example, the high lubricity of TiN may be beneficial to built-up edge during machining, Al_2O_3 may be beneficial to promote inertness and suppress coating of the tool, and TiC may be used to resist abrasion [78]. The total thickness of these multi-layer coatings is less than 10 mm and the thinner layers are instrumental in producing harder coatings [79]. Available machining performance data for these coatings are primarily for conventional test materials like ductile iron, aluminium, various grades of steel. The performance characteristics of multi-layer coatings in the processing of new materials such as titanium and nickel aluminides are as yet unknown.

There is a need for a standardized, computer-based system for the synthesis of process parameters for the deposition of TiN films with required mechanical and microstructural properties. An artificial intelligence approach may be feasible for the construction of such systems.

9. Conclusion

An attempt has been made to review the process and metal cutting performance of TiN film. Both CVD and PVD processes have been discussed in detail and the important parameters of the deposition processes have been identified. A review of available literature on the metal cutting application of TiN-coated tools indicates its widespread use with substantial improvements in metal cutting performance. Various failure modes of cutting tools have also been discussed. It is perceived that the advent of new high-strength materials will provide a new testing ground for the metal cutting capabilities of TiN films.

Acknowledgement

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