APPLICATION OF CVD AND PVD TECHNOLOGIES TO CUTTING TOOLS, AND EVALUATION OF TOOL FAILURE MODES

Dr. Deepak G. Bhat
Manager, Technology Marketing and Commercialization
UES, Inc., Dayton, OH 45432, USA

ABSTRACT

Progress in the vapor deposition technologies in the last decade has led to the introduction of many new and advanced coatings and processes for applications to metal-cutting tools. This paper presents an overview of the cutting tool materials, their properties and various methods of applying hard coatings. Recent developments in superhard wear-resistant coatings and supersoft lubricant coatings for cutting tools are briefly reviewed. Furthermore, the paper provides a description of the "systems" approach to cutting tool material selection, which is increasingly being adopted by the manufacturers and users of tools in the machining of various materials. The aspects of coating selection, based on optimizing the property requirements in the increasingly complex metal-cutting situations, is presented. Finally, the relationship between the various failure modes of coated cemented carbide cutting tools and the application-specific tool selection criteria is discussed.

RESUMEN

El desarrollo en las tecnologías de deposición en fase vapor en la última década ha llevado a la introducción de muchas nuevas y avanzados recubrimientos y procesos para aplicaciones a herramientas metálicas de cortantes. Este articulo presenta una visión global de los materiales de herramienta de corte, sus propiedades y varios métodos de depositar recubrimientos duros. Recientes desarrollos en recubrimientos superduros resistentes al desgaste y recubrimientos lubricantes superblandos para las herramientas de corte son brevemente repasados. Además, el articulo proporciona una descripción acerca de los "sistemas" para la selección de materiales para herramientas de corte, que es adoptando cada vez más por los fabricantes y usuarios de herramientas en el maquinado de varios materiales. Se presentan los aspectos de selección del recubrimiento, basados en perfeccionar las propiedades requeridas en el complejo aumento de las condiciones de corte de metal. Finalmente se discute, la relación entre los varios modos de falla de recubrimientos de carburo cementado en herramientas de corte y el criterio de selección de la herramienta para una aplicación especifica.

Palabras Claves:

Invited Paper presented at Il Jornadas de Ingenieria Metalurgica y Ciencia de Los Materiales, Universidad Central de Venezuela, Caracas, Venezuela, November 1997.

Introduction:

Cutting tools are a very important class of advanced engineering materials for the manufacturing technologies. A variety of cutting tool materials are used to machine various materials in the manufacture of useful components. It has been estimated that the worldwide market for cutting tools is on the order of $10-12 billion, and comprises cutting tools made of cemented carbides, high speed steels, ceramics, cermets, polycrystalline diamond and cubic boron nitride, and other types of tools (Conference, 1996). Of these, nearly 40-45% of the tools are cemented carbides and an equal amount of high speed steel tools. The application of hard, wear resistant coating on cutting tools began in mid-1960s, and today nearly 70% of cutting tools are coated. Thus, coatings have become an integral part of modern cutting tool materials, and a considerable research and development effort is expended on the development of new coating techniques and materials for improved cutting tools.

The earliest methods used for imparting increased surface hardness and wear resistance to cutting tools involved heat treatments, such as carburizing and nitriding, when the tools were essentially made of carbon steels and high speed steels. In mid-1960s, chemical vapor deposition (CVD) was used for the first time to deposit thin coatings of hard, refractory compounds on cutting tools, to provide increased hardness, chemical stability and wear resistance. The physical vapor deposition (PVD) techniques were introduced in the commercial markets in the late 1970s and early 1980s, and now enjoy an almost equal status with the CVD techniques in this market.

This paper reviews the application of the CVD and PVD methods for depositing hard coatings to cutting tools, types of coatings used for metal-cutting applications, and examines the typical failure modes of cemented carbide tools during machining.

Types of Cutting Tool Materials:

The various cutting tool materials may be classified as follows:

1. High Speed Steels: These are alloys of iron and carbon, containing chromium, tungsten, molybdenum, titanium and other refractory metals. The high speed steels are characterized by high hardness, strength, wear resistance and high toughness. The presence of carbide-forming refractory elements imparts significant high-temperature hardness to these steels, thereby making them suitable for machining other materials. Because of the fact that these are iron-base materials, their useful service temperature is limited by the softening point of the iron alloy matrix.

2. Cemented Tungsten Carbides: These may be considered a type of composite materials, in which micron-size grains of WC (and other carbides, such as TiC, TaC, NbC) are bonded together by a metallic binder (usually Co) in a powder metallurgical process. These materials came into prominence during the World Wars, when the German company Krupp developed and manufactured these materials to meet the increasing demands of machining advanced alloys for the war effort. An excellent review of the early history of the cemented carbide tools (also known as hardmetals) is given by Brookes (Brookes, 1996). After the World War II, the German technology became available to other countries, and

grew rapidly in the following decades. Today, nearly half the cutting tools used in the world contain cemented tungsten carbide.

3. Cermets: These are another class of hard materials similar to cemented tungsten carbide. These materials are based on TiC and TiN, with a multi-component alloy binder consisting of Co, Ni, Mo and W. The term ‘cermet’ - derived from the words CERamic and METal - was first applied to these materials by the Japanese, because these materials consist of refractory ceramic particles (TiC, TiN) in a metallic alloy binder. Strictly speaking, even cemented tungsten carbide can also be called a cermet; however, it has now been conventionally accepted that cermets represent the TiC/TiN base cutting tools, while cemented carbides (or hardmetals) are WC-base cutting materials.

4. Ceramics: Ceramics are excellent candidates for cutting tool materials because of their high hardness, thermal stability and strength. Typical ceramic cutting tools include Al_2O_3, Al_2O_3/TiC, Si_3N_4, SiAlON, Al_2O_3/SiC whisker composite, etc. These materials are manufactured by the conventional ceramic processing methods, such as hot pressing, sintering, hot isostatic pressing, and sinter-hot isostatic pressing (sinter-HIP).

5. Superhard Materials: These include polycrystalline diamond and polycrystalline cubic boron nitride. Diamond is the hardest material know to man, and cubic boron nitride is the second hardest. Naturally, these materials make excellent cutting tools. The discovery of a method to produce synthetic diamond by high-temperature, high-pressure synthesis led to a large market for the synthetic diamond in the grinding and metal-cutting applications. Today, several companies offer these tools; however, the three major global companies are DeBeers (South Africa), General Electric (USA) and Sumitomo (Japan).

Thus, there is a wide variety of materials which qualify as cutting tools. It is instructive, therefore, to consider the unique properties required of cutting tool materials.

Property Requirements for Cutting Tools and Tool Coatings:

It is useful to examine together the desirable properties of cutting tool materials and coatings, because it will be manifest that these requirements overlap considerably, although each of them (the tool substrate and the coating) have their own unique characteristics as well. Table 1 lists the most important properties of these materials.

Certain common characteristics of the tool materials and coatings become apparent. Both require high hardness, fracture toughness and abrasive wear resistance. Because of the high thermal stresses and impacts involved in certain machining operations such as milling, and the machining of certain types of components such as castings and irregular parts, the tool material is required to possess high thermal shock resistance, and in many cases, a high deformation resistance. High transverse rupture strength is also a critical requirement. Often, the work-piece material reacts chemically with the tool at the high cutting temperature, causing a chemical erosion of the tool due to the dissolution of the tool material in the work-piece. Therefore, high chemical stability is an important property of the tool material. Typical properties of a cemented carbide cutting tool are given in Table 2. The table also includes nominal properties of other superhard tool materials for comparison.

Unfortunately, all the required or desired properties cannot be obtained in a tool material under all machining conditions. Certain materials are relatively easy to machine, while others are extremely difficult. Most steels and cast irons, and non-ferrous materials such as aluminum alloys are easier to machine than materials such as stainless steels, heat-treated steels and cast irons, titanium alloys and superalloys. This means that, depending on the material being machined, a given tool material may or may not perform adequately unless its properties are augmented by some methods. The application of hard coatings by various means is now widely used for this purpose.

Before we examine the currently used techniques for applying hard coatings to tools, it is useful to study the typical microstructural characteristics of common tool materials. Since the cemented carbide tools are most commonly used today, this paper will restrict the discussion to these tools.

A typical microstructure of a cemented tungsten carbide tool is shown in Fig. 1. As stated earlier, a cemented carbide tool consists of WC, cobalt, and optional additions of other cubic carbides, such as TiC, TaC and NbC. Often during the manufacture of these materials by powder metallurgical techniques, certain undesirable phases may be formed in the microstructure. The most common is the eta phase ($M_{12}C$ or M_6C, where M = Co+W). The eta phase is formed due to a loss of carbon from the binder phase during sintering (Johansson, 1983), and is usually found near the tool surface. The eta phase is denser than the cobalt binder, resulting in the formation of voids in this region. These voids often link together due to crack propagation during machining and cause micro-fracture of the cutting edge (Bhat, 1986). This situation can be corrected during the sintering process by preventing decarburization of the carbide.

The eta phase can also form during the CVD coating process if care is not taken to maintain a proper composition of reactive gases in the initial stages of coating. Bhat, et al (Cho, 1986) showed that a deleterious form of eta phase ($M_{12}C$) forms when a highly decarburizing environment exists in the CVD furnace during the deposition of the TiC or TiCN coating. This situation can be corrected by properly balancing the relative concentrations of H_2 and $TiCl_4$ (Cho, 1986; Cho, 1989). or by depositing an initial layer of TiN (Weiner, 1998).

Going back to the discussion of the microstructure of cemented carbide, the addition of cubic carbides such as TiC, TaC and NbC imparts high-temperature deformation resistance as well as hardness to the carbide. At the same time, it is necessary to balance the strength and hardness with adequate fracture toughness which is required for tools used in milling. One method is to increase the cobalt binder content from the typical 6% to about 8-12%. Often, however, it is found that the fracture toughness of the tool is not sufficient to prevent catastrophic fracture of the cutting edge when particularly severe impact conditions are encountered in the milling of certain alloys. Cutting tool companies have responded to this problem by developing grades with a gradient of binder concentration from the near-surface region to the bulk of the tool. As shown in Fig. 2, the substrate region near the surface of the tool has been depleted of the cubic carbide phase, and enriched in the cobalt binder, whereas the bulk composition is very uniform. In this way, a surface region of very high fracture toughness is created which effectively resists crack propagation during milling.

The adhesion of the wear-resistant coating to the tool surface is the most critical requirement, because the coating cannot be effective unless it is well-bonded to the tool. In the CVD coating processes, it is relatively easy to achieve good adhesion by developing a diffusion-induced interface between the coating and substrate. The task is more difficult in the PVD processes, mainly because of the much lower coating temperatures (450-500^{o}C as compared to 950-1050^{o}C in CVD). Therefore, a high degree of surface cleanliness is required for tools coated by PVD. Recent advances in the PVD process technologies now provide the means to deposit initial "bonding" layers which enhance the coating adhesion.

Techniques of Hard Coating for Cutting Tools:

There are essentially two techniques used in the industry: chemical vapor deposition (CVD) and physical vapor deposition (PVD). Each of these two technologies include several different techniques. These are summarized in Table 3.

The most commonly used CVD technique is the conventional CVD, which refers to CVD processes carried out at typical temperatures of around 1000^{o}C. Most of the conventional hard coatings can be deposited at the atmospheric pressure as well as at the more preferred low pressure (50-300 Torr). Plasma-assisted CVD operates at a lower temperature (500-700^{o}C), because the creation of a plasma environment enhances the reactivity of precursor gases. Therefore, useful chemical reaction occur at a lower temperature to form the hard compounds (Bhat, 1989). This technique is not as widely used for cutting tools as in the microelectronics industry, because of the relatively high cost of the equipment and marginal advantages in properties of the coatings on cemented carbide tools.

The medium temperature CVD (MTCVD) technique was developed in Europe to deposit coatings of TiCN and TiN using metal-organic compounds of titanium, in order to make the technique suitable for steel tools which cannot withstand the conventional CVD temperatures (Bonetti-Lang, 1982). Metal-organic CVD and Laser CVD techniques are not used for hard coatings at this time, but present great potential in this application because they offer the advantage of lower coating temperature, and the ability to synthesize new hard coating materials not feasible with conventional CVD.

In the case of PVD techniques, the most commonly used processes today are evaporation and sputtering. Electron beam evaporation of a titanium ingot in a vacuum chamber and reaction with a nitrogen plasma to deposit TiN was the first successful application of PVD for cutting tools. Later on, deposition by sputtering from a solid target was used, and this technology has been considerably advanced during the last decade by several groups in Europe, Japan and the U.S. Today, many variations of sputtering techniques are used commercially.

Another PVD technique which has become quite common today is the cathodic arc evaporation. In this technique, an arc is struck across a solid metal target by applying a high potential. The arc spot is then magnetically steered across the target surface, causing evaporation of the target. The evaporated metal is drawn into the vacuum coating chamber under an electromagnetic field, and reacted with a suitable gas to form the coating. After some initial technological problems related to the control of the arc and formation of the undesirable "macro-particles" from the metal target, the technology has now advanced to provide excellent coatings for cutting tools and other applications. An electromagnetic filter is used to trap un-ionized liquid metal droplets (macro-particles) while bending the ionized plasma into the coating chamber by applying a suitable electric field to the deflecting magnetic coils. A schematic diagram of a filtered cathodic arc PVD coating system is shown in Fig. 3 (Gorokhovsky, 1995).

Hard Coatings Deposited by the CVD and PVD Techniques:

A wide variety of hard coatings, such as carbides, nitrides, borides, oxides and their mixtures can be deposited by these techniques. For cutting tool applications, however, only certain compounds are suitable, because of their unique properties and ease of deposition. Table 4 summarizes the various tool coatings in use today. These coatings exhibit excellent properties, which are required for metal-cutting applications, such as high hardness, chemical inertness, and wear resistance. Selected properties of some of the common hard coating materials are given in Table 5.

A careful examination of the data in Table 5 shows certain common characteristics of these materials. All these compounds have a high melting point, elastic modulus and hardness. These properties determine the ability of the coating to provide the necessary wear resistance and thermal stability during machining. An important property which determines the *relative* chemical stability of these compounds is the standard free energy of formation. The more negative this value, the more stable the compound is. It is, therefore, immediately clear that the oxide coatings - Al_2O_3 and ZrO_2 - are significantly more stable than the carbide and nitride coatings. The implication of this property is that at higher cutting temperatures, it is desirable to have an oxide coating on the cutting tool.

Another important property of the coatings is the coefficient of thermal expansion, since this property determines the interfacial thermal mismatch stress between the coating and the substrate. A closer match of expansion coefficient of the coating and substrate is desirable for improved adhesion of the coating to the tool. The thermal conductivity of the coating is also important, in that it determines how the heat generated in the cutting operation will be dissipated. A high thermal conductivity value indicates that the heat will be dissipated into the tool material, causing it to soften at higher cutting speeds. A lower thermal conductivity of the coating or the tool material allows the heat to be transferred back to the metal chip, which is a more desirable method of heat removal.

Often, it is necessary to combine typical properties of each coating to provide a multi-functional coating combination to machine certain materials. This approach has led to the practice of depositing multi-layered coatings of different compounds in a specific sequence. Thus, today, most of the CVD-coated cemented carbide cutting tools contain multiple layers, such as TiC or TiCN, followed by TiN, or Al_2O_3, or similar combinations. In addition, it is necessary to take into account the specific requirements of a given machining operation or the material being machined, in order to select the proper coating or coating combination for efficient machining. The critical role of the "systems approach" in designing the proper combination of tool, coating, tool geometry and machining conditions has been discussed by several experts (Katbi, 1998; Narasimhan, 1995; Quinto, 1996).

Tool Selection Criteria:

The shift towards using a "systems approach" for the selection of a coating for tools led to the realization that other aspects of cutting tools and applications must also be dealt with in a similar manner. The selection of a cutting tool for a given application used to be quite complex and confusing. Over the last decade or so, the manufacturers and users of cutting tools have come to understand the inter-relationship between the various elements of a cutting tool "system," which includes not only the tool substrate, but also, the coating, geometry, tool holder, cutting fluid and the work-piece material. Figure 4 shows the elements of a complete cutting system, and includes the various sub-elements which influence the selection of an optimum combination of workpiece, cutting tool, coating, tool geometry and coolant.

A better, internationally accepted, system of classification for different work-piece materials (the ISO Codes), has been adopted by the tool manufacturers, which makes it possible to have a greater understanding of the synergy between various elements of a cutting tool system. The ISO standard classifies the work-piece materials in three categories, with designated color codes. For example, carbon and alloy steels are marked in BLUE, stainless steels, titanium and other high-temperature alloys are designated in YELLOW, and cast irons, aluminum and other non-ferrous alloys, plastics, etc., are designated in RED color. The recommendations of cutting tools for these materials then follow the same color-coding scheme, which makes it much easier for the tooling engineer or machinist to select the appropriate tool for the job.

A consideration of the machinability of various materials involves an understanding of their abrasiveness, plastic flow and work hardening characteristics, chemical reactivity and microstructure. The selection of a cutting tool material, therefore, must take into account the response of the workpiece material, as well as the properties and geometry of cutting tool, cutting parameters and coolants. With a good understanding of the inter-relationship between the various elements of a cutting tool system, the tool selection process becomes much simpler and systematic, and allows a machinist to logically select the proper tool and other requirements (coating, chip breaker, coolant, etc.) for optimum tool performance. A typical tool selection chart is shown in Fig. 5 for machining of stainless steel. It shows the recommended ISO classification of the tool substrate, cutting fluids, types of tool failures encountered for a given machining application, and the application ranges of various coated cutting tool materials. Using a chart like this, tool selection for a given operation can be made systematically. The steps in this selection process may be summarized as follows:

1. 1. Select work-piece material by the color code,
2. 2. Select the carbide tool grade closest to the midpoint of the machining operation range,
3. 3. Select the appropriate chip-breaker style,
4. 4. Select tool insert shape, size and coating,
5. 5. Conduct machining test to verify selection,
6. 6. Use failure mode analysis guide to optimize tool selection, and repeat the process until the most optimum set of parameters is obtained.

Most major cutting tool companies now offer charts and guidelines to assist the machinist in the selection of their cutting tools. These guidelines are very useful in improving tool performance and productivity. Eventually, however, the tools fail by one or more causes when their useful life comes to an end. An understanding of the typical failure modes of tools is useful in understanding the role of various factors which together comprise the "cutting tool system."

Tool Failure Modes:

The manner in which the cemented carbide cutting tools fail in service has been the subject of study for many years, and will continues to be so as long as new materials are developed for improved productivity. Numerous papers have documented a variety of tool failures, and developed methods to understand the causes and find remedies. The relationship between the cutting parameters and tool failure is shown in Fig. 6 (Quinto, 1996). The cutting speed is related to the thermo-chemical stability, and the feed rate is related to the mechanical properties (strength and fracture toughness) of the tool material. At higher cutting speeds, more of the heat generated in the cutting is transferred to the tool, setting up inter-diffusion between the tool and workpiece, and dissolution of the tool. This leads to chemical wear of the tool. At higher feed rates, high mechanical stresses are induced in the tool cutting edge, leading to fracture of the tool. The most desirable form of tool failure is progressive wear caused by abrasion, because this type of wear is much more predictable than other failure modes. This requirement essentially defines the useful boundaries of the optimum operating zone for cutting parameters for a given tool material. Thus the failure mode diagram shows the zones of tool failure from which a safe zone for predictive tool performance can be derived.

An excellent documentation of tool failure modes and guidelines for a proper selection of tools has been published by Valenite, Inc., of Madison Heights, Michigan, USA (Lathe, 1997). These failure modes depend on a variety of factors, which include not only the substrate material and coating, but also the cutting parameters, cutting machines and use of coolants during machining. Thus, a given failure mode may be the result of a combination of factors, not all of which may relate to the coating. A proper analysis of a tool failure requires examining all the possible causes, and then determining the most probable cause. The most common cutting tool failure modes can be listed as follows:

1. 1. Flank/Nose and Crater Wear
2. 2. Built-up Edge (Chip Welding)
3. 3. Micro-chipping of Cutting Edge
4. 4. Excessive Depth-of-cut Notching
5. 5. Fracture
6. 6. Thermal Cracking
7. 7. Coating Delamination (Spalling)
8. 8. Poor Surface Finish
9. 9. Workpiece Chatter and Vibrations
10. 10. Unacceptable Chip Formation/Control

Several of these failure modes are illustrated in Fig. 7, taken from ref. 14. Of these various modes, most are caused by an improper tool selection, and some by the machining equipment, the nature of the workpiece material or improper coolant (cutting fluid) use. In this paper, we are mainly concerned with the role of hard coatings in preventing or eliminating some of the failure modes. Therefore, the following discussion will be limited to only those failure modes which can be influenced by a proper selection of a coating. As shown in Fig. 4, and discussed earlier, one cannot easily isolate the effect of one of the elements and ignore the synergistic effect of other elements of the cutting tool system in evaluating tool failure. However, certain failure modes are directly influenced by a coating. These include wear, edge build-up, thermal cracking, delamination and surface finish. We will, therefore, discuss those types of failures in the following.

Flank and Nose Wear: The predominant cause of wear of a cutting tool is abrasion. Abrasion results from the rubbing of the tool cutting edge and flank with the workpiece material during cutting. As with other types of abrasive wear, flank and nose wear are accelerated at higher cutting speeds or when there is excessive heat build-up at the cutting edge. The presence of abrasive second-phase particles in the workpiece material also accelerates tool wear. The application of hard coatings is particularly effective in this case, because these coatings have much higher hardness as compared to most workpiece materials. Thus, it can be seen from a reference to Table 5 that abrasive wear can be reduced by using a TiC or TiCN coating, especially at lower cutting speeds. If the tool temperature increases during cutting, a coating of TiN is more effective, because TiN is chemically more stable than TiC or TiCN. Also, TiN has a lower coefficient of friction than TiC or TiCN. This has the effect of reducing heat build-up at the cutting edge. When the cutting temperature increases significantly, as often happens in the machining of ferrous alloys, a coating of aluminum oxide is most effective. Alumina not only has a better hot hardness, but because it is an insulator, it prevents heat build-up in the cutting tool and tends to transfer the frictional heat into the chips. Another effective method of reducing flank and nose wear is by selecting a proper insert style, chip breaker, and rake and lead angles of the tool holder and use of coolants.

Crater Wear: Crater wear is sometimes also referred to as chemical wear, because it is caused by the chemical dissolution of the tool material into the metal chip during cutting. As the chips slide across the top surface of the tool (the rake face), they rub against the tool, and cause abrasive wear. At the same time, an inter-diffusion of the elements from the tool and chip occurs, leading to a slow cratering of the rake surface near the cutting edge. The formation of the crater behind the cutting edge causes a weakening of the edge, leading to edge fracture. Again, a coating such as TiN, which has a greater thermal stability than TiC or TiCN, reduces crater wear. Since this type of wear is caused by the rubbing of the chip on the rake surface, a smoother coating is more effective in reducing crater wear than a rough coating. Another effective method is to use a chip breaker geometry that minimizes contact time and area between the chip and the rake face, and breaks the chip quickly. Reducing the cutting speed also helps reduce crater wear.

Built-up Edge (Chip Welding): This condition is caused when a part of the metal chip sticks to the tool edge. This may happen either due to interdiffusion of material from the tool and chip, or due to a rough tool surface. Certain soft materials, such as aluminum alloys, tend to stick to the tool more readily than other alloys. Built-up edge condition often occurs when the cutting action is not very efficient, either due to a slower cutting speed or feed rate, or improper tool geometry. TiN coating is found to be most effective in reducing chip welding. It was shown by Bhat, et al (Bhat, 1995) in the case of a diamond-coated cemented carbide cutting tool that polishing the cutting edge of the coated tool dramatically reduces this problem in the machining of aluminum alloys. A sharper cutting edge also provides a more efficient shearing action, and reduces the chip welding tendency.

Thermal Cracking: Thermal cracking is caused when the cutting edge experiences rapid temperature fluctuations and cyclic mechanical stresses during cutting. This condition occurs during milling or interrupted cutting, when the tool repeatedly enters and exits the cut at a high speed, and experiences thermal fatigue. This failure mode is, therefore, directly related to the fracture toughness of the tool substrate. However, the coating can play a significant role in reducing the thermal cycling and initiation of cracks. Coatings deposited by CVD techniques typically impart a small residual tensile stress on the surface of a cutting tool, whereas a PVD coating imparts a significant residual compressive stress. Therefore, it is found that a PVD TiN-coated tool shows greater resistance to thermal cracking than a CVD TiN-coated tool in the milling of steel.

Delamination (Spalling): This is a critical failure mode caused by poor adhesion of the coating to the tool. Poor adhesion can occur due to a number of factors during the coating process. The most common reasons for poor adhesion are: improper insert cleaning and preparation prior to coating, unacceptable surface condition caused by pitting, staining or cobalt leaching during sintering or grinding steps, contamination during the initial stages of the coating process, and finally, excessive cutting force leading to microcracking of the coating or deformation of the cutting edge. Most commonly, the cause of poor adhesion is improper tool preparation before coating. It is obvious that if a part of the substrate is exposed due to a loss of coating, rapid wear of the tool would result, leading to unpredictable tool failure.

Poor Surface Finish: In most situations, poor surface finish is caused by improper cutting conditions and/or incorrect selection of tool geometry. However, it has been shown that often a coating of TiN improves surface finish under optimum machining conditions because of the lubricity of the coating. TiN has a low coefficient of friction, which helps reduce tool tip temperature and removes chips more efficiently from the cutting zone. It also resists build-up of metal at the cutting edge. All these factors lead to improved surface finish. Recently, soft, solid lubricant coatings have been applied to cutting tools for improved surface finish and tool life. It is believed that these coatings provide an improvement in tool life due to a reduction in tool wear. These coatings are discussed in the next section.

In summary, the failure modes of cutting tools can be understood by examining all the factors which contribute to the performance of the cutting tool as a system - substrate, coating, tool geometry, cutting parameters, work-piece material and lubrication. Coatings play a significant role in the performance of a cutting tool, due to their superior hardness, wear resistance, thermal stability and other properties.

New Developments in Superhard and Supersoft Coatings:

During the last decade, significant progress was made in the development of a new class of coatings, known generally as superhard coatings. These include mainly the thin-film diamond, cubic boron nitride, carbon nitride and superlattice coatings. These coatings have tremendous potential for significant improvements in the performance of coated components because of their excellent properties. Although some of these coatings have almost reached the point of commercialization, they are not yet well established in the metal-cutting industry. The main reason is that the deposition processes have not yet overcome many technological problems for low-cost, reliable coatings.

Thin film diamond coatings have almost reached the commercialization stage, and quite a few companies now offer diamond-coated cutting tools for various non-ferrous machining applications. The most commonly used deposition methods for diamond coatings include hot-filament CVD (HFCVD), microwave plasma CVD (MWCVD) and plasma arc-jet CVD (Bhat, 1994). Other methods, such as laser CVD and combustion CVD have also been applied on a limited scale. The main difficulty with diamond is that it is deposited at temperatures in excess of 850 ^{o}C, which makes it unsuitable for high-speed steel tools. In the case of cemented carbide tools, the biggest challenge was to overcome the deleterious effect of cobalt binder in the substrate, which tends to graphitize the diamond and destroys adhesion. A variety of techniques have been used to prevent the interaction of cobalt with diamond film, which primarily depend on chemical methods to remove cobalt from the surface of the carbide substrate (Bennett, 1996; Bhat, 1998). Manipulation of the carbide surface crystal morphology during sintering has also been used to improve the adhesion of diamond to the substrate (Grab, 1995). The deposition of cubic boron nitride thin films to carbide substrates has been equally difficult, but in this case, the primary reasons include the difficulty of synthesizing the pure cubic phase of boron nitride, and the presence of a very large internal stress in the coating which increases with the thickness and cubic content of deposited BN film. This difficulty has prevented the successful deposition of a uniform film of cubic boron nitride of thickness exceeding about a micron. Initially, a combination of different CVD methods (HFCVD+MWCVD, ECR-MWCVD, Laser ablation, etc.) were attempted to synthesize cubic BN, and recently PVD methods are being studied with some success in the laboratory. Essentially the same situation exists for the carbon nitride coatings, which are unlikely to find useful applications in metal-cutting. However, these films show significant promise in other tribological applications.

The superlattice coatings are based on the idea of sequential deposition of ultra-thin layers of two compounds with a close match of lattice parameters, such that they can develop coherent interfaces leading to a superlattice structure. Most of the work in this area has been done on refractory metal nitrides. The most promising of these materials include TiN/NbN, TiN/AlN, and TiN/VN. These coatings are typically deposited by reactive magnetron sputtering, and have demonstrated significant improvements in hardness and wear resistance as compared to TiN and other conventional hard coatings (Madan, 1998).

Supersoft coatings are a recent development, spurred by an increasing interest in dry machining. The growing concern about the disposal of, and environmental pollution caused by, cutting fluids or coolants used in machining has led to the investigation of alternative methods of machining. These methods either rely on benign water-based coolants or strive to eliminate coolants altogether. Another approach, which has its origins in the research on dry film lubricants for use in aerospace tribological applications, has recently found surprising application potential in metal-cutting and metal-forming tools. Coatings of supersoft materials based on the metal dichalcogenides have been recently developed for cutting tools. The most commonly known coatings in this category include MOVICÔ and MoSTÔ, which are commercially available on a limited scale. These coatings contain MoS_2, a well-known dry lubricant which has been used in powder and spray form for decades. The coating is deposited by magnetron sputtering from a solid target on to the surface of tools. Recent results show that this coating works better in combination with a conventional hard coating, such as TiN, TiCN or TiAlN (May, 1998). It has been proposed as a substitute for coolants used in the high-speed machining of aluminum alloys, where it has perhaps the most promising application. This technology is not fully mature as yet, since it has been tested only on a very limited scale using only round-shank tools such as end-mills, drills and taps. It is expected that further advances in the technology of supersoft coatings for machining and forming applications will take place, such that these coatings can be applied on a broader scale.

A variation of this approach has been introduced by Balzers, in which a relatively hard coating of WC and carbon is deposited by reactive magnetron sputtering (derflinger, 1998). This coating has a Knoop hardness of about 1,000 kg/mm^2, and consists of an amorphous carbon matrix with a honeycomb morphology of nanocrystalline WC grains. The coating has a coefficient of friction on the order of 0.15, and is found to work well in drilling applications.

Summary:

A historical perspective of the various cutting tool materials, and especially of the various coating materials and technologies, has been given. Essential properties of the tool materials and coatings for cutting tools were discussed. The paper highlighted the complex relationship between the tool materials, coatings, and cutting conditions in metal cutting. A a detailed overview of the typical failure modes of cemented carbide cutting tools was given. Advances in superhard and supersoft coatings for metal-cutting applications were briefly discussed.

Acknowledgements:

The author is indebted to many former colleagues at Valenite, Inc., for their interest and assistance in the preparation of this paper. Thanks are especially due to Mr. Krishnan Narasimhan, Mr. Douglas Doney and Mr. Karl Katbi, for providing technical data and permission to use the cutting tool failure mode charts. Thanks are also due to Dr. Henk van den Berg, General Manager of Research and Development at Widia GmbH, for providing information on plasma CVD of hard coatings, and to Dr. Hans Hintermann, Swiss National Science Foundation, for his friendship, mentorship and vaulable guidance during the last several years. Finally, the author is deeply indebted to Professor Dra. Mariana Staia of the Department of Metallurgy, Central University of Venezuela, Casacas, for inviting the author to present a talk and a workshop on hard coatings at the 25th Anniversary celebration of the School of Metallurgy.

References:

Bennett S.L., D.G. Bhat & D.G. Johnson. 1996. U.S. Patent # 5,560,839.

Bhat D.G., D. G. Johnson, A. P. Malshe, H. Naseem, W. D. Brown, L. W. Schaper & C.-H. Shen. 1995. *Diamond and Related Materials*, **4** 921.

Bhat D.G., in Surface Modification Technologies - An Engineer's Guide. 1989. Ch. 2 (T.S. Sudarshan, Ed.), Marcel Dekker, Inc., New York, NY.

Bhat D.G. 1994. Materials Technology, **9(11/12)** 253 ().

Bhat D.G., S.L. Bennett & D.G. Johnson. 1998. U.S. Patent # 5,713,133.

Bhat D.G., T. Cho & P.F. Woerner. 1986. *J. Vac. Sci. Technol.* A, **4(6)**, 2713.

Bonetti-Lang M., R. Bonetti & H.E. Hintermann. 1982. *Refractory and Hard Metals*, **1**, 161.

Brookes, K.J.A. 1996. World Directory and Handbook of Hardmetals and Hard Materials, Sixth Edition, International Carbide Data (U.K.).

Cho T., D.G. Bhat & P.F. Woerner. 1986. *Surf. Coat. Technol.*, **29**, 239.

Cho T., K. Narasimhan & D.G. Bhat. 1989. U.S. Patent 4,830,886.

Conference on Global Trends and Business Outlook for Cutting Tool Materials, Gorham Advanced Materials Institute, Atlanta, GA (1996).

Derflinger V., H. Brändle and H. Zimmermann. April 1998. Paper presented at the International Conference on Metallurgical Coatings and Thin Films, San Diego, CA.

Gorokhovsky V.I. 1995. U.S. Patent # 5,435,900.

Grab G., W. M. Melago, E. J. Oles, G. D. Murray, C. E. Bauer & A. Inspektor . 1995. World Patent No. WO 95/15258.

Johansson T. & B. Uhrenius. February 1983. *Met. Sci.*, p. 83.

Katbi K. 1998. Modern Machine Shop, January 1998, 88.

Lathe Insert Application Guide, Publication No. I-LIA100, Valenite, Inc., Madison Heights, Michigan, USA, July 1997.

Madan A. 1998. Conference on World Cutting and Machine Tools Markets-1998, organized by Gorham Advanced Materials Institute, Tampa, FL.

May R.B. 1998. Conference on World Cutting and Machine Tools Markets-1998, organized by Gorham Advanced Materials Institute, Tampa, FL.

Narasimhan K., S.P. Boppana & D.G. Bhat. 1995. *Wear*, **188**, 123.

Quinto D.T. 1996. *Int. J. Refractory Metals & Hard Materials*, **14**, 7.

Weiner M. 1998. Cutting Tool Engineering, **50(1)**, 24.

LIST OF FIGURES

Table 1: Desirable Properties of a Tool Material and Tool Coating

PROPERTIES OF A TOOL SUBSTRATE	PROPERTIES OF A TOOL COATING
_ High Hardness and Hot Hardness	_ High Hardness and Hot Hardness
_ High Abrasive Wear Resistance	_ High Abrasive Wear Resistance
_ High Fracture Toughness	_ High Fracture Toughness
_ High Deformation Resistance	_ High Adhesion to Tool Substrate
_ High Transverse Rupture Strength	_ High Thermal Fatigue Resistance
_ High Thermal Shock Resistance	_ Low Thermal Conductivity
_ High Chemical Stability at High Temperature	_ High Chemical Stability Against Work-piece Material
	_ Low Coefficient of Friction

Table 2: Comparison of Properties of Cemented Carbide and Other Superhard Materials

Properties	Carbide WC + 6% Co	Polycrystalline Diamond (PCD)	PoₗycrystallineCubic Boron Nitride (PCBN)	Natural Diamond
Density, g/cm^3	14.8	3.43	3.12	3.52
Knoop Hardness, GPa	13	50	28	57-104
Young's Modulus, E, GPa	620	925	680	1141
Modulus of Rigidity, G, GPa	250	426	279	553
Poisson's Ratio, ν	0.22	0.086	0.22	0.07
Transverse Rupture Strength, MPa	2,300	> 2,800	600-800	700-1,700
Compressive Strength, MPa	5,900	4,740	3,800	8,580
Fracture Toughness, K_{IC}, MN/m$^{3/2}$	12	6.89	10	3.4
Thermal Expansion Coefficient, α, 10^{-6}/K	5	3.8	4.9	3.5
Thermal Conductivity, W/mK	95	120	100	500-2000

Table 3: Techniques Used For Depositing Hard Coatings on Cutting Tools

CVD TECHNIQUES	**PVD TECHNIQUES**
Conventional CVD - Atmospheric Pressure - Low Pressure CVD	Evaporation - Electron Beam PVD - Cathodic Arc PVD
Plasma Assisted CVD (PACVD)	Magnetron Sputtering
Medium Temperature CVD (MTCVD)	Ion Beam Assisted Deposition (IBAD)
Metal-Organic CVD (MOCVD)	Hybrid PVD, Pulsed Plasma PVD
Laser CVD (LCVD)	Laser PVD (LPVD)

Table 4: Hard Coatings for Cutting Tools Deposited by CVD and PVD Techniques

COATINGS	CVD	PVD
Carbides	TiC, WC	TiC, B_4C, Cr_XC_Y, ZrC, WC
Nitrides	TiN, ZrN, HfN	TiN, ZrN, CrN, NbN, VN, TiAlN, TiZrN
Carbonitrides	TiCN, ZrCN	TiCN, ZrCN
Oxides	Al_2O_3, ZrO_2	Al_2O_3, ZrO_2
Multilayer Coatings	TiC/TiN, TiCN/TiN, TiC/Al_2O_3, TiC/Al_2O_3/TiN, TiCN/Al_2O_3, TiCN/Al_2O_3/TiN, [TiCN/Al_2O_3]$_n$	TiCN/TiN, TiAlN/TiN, TiN/NbN (superlattice coating)
Multiphase Coatings	Al_2O_3 + ZrO_2	MoS_2/TiN, MoS_2/Metal
Other Coatings	Diamond, TiB_2, cBN (potential)	MoS_2, WS_2 (soft lubricant coatings), Hard DLC (a-C)

Table 5: Selected Properties of Typical Hard Coatings for Cutting Tools

PROPERTY	**TiC**	**TiN**	**HfN**	**ZrN**	**Al_2O_3**	**ZrO_2**
Melting Point, K	3340	3220	3660	3250	2330	
Density, g/cc	4.9	5.4	13.9	7.4	4.0	5.6 ❖
Crystal Structure	Cubic	Cubic	Cubic	Cubic	Hexagonal	Monoclinic
Specific Heat, J/kg/K	550	600	200	400	850	500
Thermal Conductivity, W/m/K	30	20	22	12	39	1.7
Coefficient of Thermal Expansion, 10^{-6}/K	7.4	9.4	6.5	7.1	8.0	7.5-12
Elastic Modulus, GPa	447	600	380	500	414	300
Hardness, kg/mm^2	2900	2000	1640	1450	2000	1500
ΔG_F, kcal/mol @298 K	- 43	- 74	- 81	- 80	- 378	- 248

- • Monoclinic ZrO_2 transforms to tetragonal phase in the temperature range 1225-1550 K; Tetragonal phase melts at 3040 K.
- • Density of the monoclinic phase; Density of tetragonal phase = 6.1 g/cm^3.