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Analysis of Ti-base Hard Coating Performance in Machining Process: A Review

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Abstract: Advantages of hard coating (hard thin film) including high hardness, lower friction coefficient and high chemical stability has attracted the attention due to its superior performance in hard machining. This study reviewed the performance of Ti-base hard coating especially TiAlN and TiCN coatings and the factors influencing the coating properties in machining process. The said coatings have a good wear resistance, lubricity between cutting tool and chip interface, high hardness, lower friction coefficient and chemically stable and is therefore suitable for coating the cutting tool. By coating the cutting tools, it will significantly improves the cutting tool life and hence increase the productivity.

Key words: Ti-base hard coating, cutting tool, machining process

INTRODUCTION

Cutting tools need to be wear resistant, hard and chemically inert to prevent chemical interaction between the cutting tool, workpiece material and cutting environment during machining process. It was found that the high hardness surface of the cutting tool increases the wear resistance of cutting tool (Kumar *et al*., 2007; Jianxin *et al*., 2011). To accomplish these objectives, some of the cutting tool is coated with single or multiple materials to increase the wear resistance and improve the performance of the cutting tool. In North America and Western Europe, it was estimated that more than half of the metal-cutting tools are coated by either Chemical Vapour Deposition (CVD) or Physical Vapour Deposition (PVD) (North, 1998).

Coating basically can increases the wear resistance, prolonged the tool life and reduces the cutting forces and cutting temperature (Jindal *et al*., 1999). It is well known that thin and/or hard coatings can reduces tool wear and improves tool life and hence the productivity (Chung-Chen and Hong, 2002; Yigit *et al*., 2008). Hard coatings such as TiN provides markedly improvements in many manufacturing processes and offer particular productivity advantages when applied to the tools used in metal-cutting operations. For examples, Tang *et al.* (2000) found a great improvement in tool life with diamond-cobalt boride composite coatings.

Similarly, Shao *et al.* (2007) found that coating could effectively reduce the formation of adhesive layers on the tool and thus prevent the formation of BUE. Liew and Ding (2008) had reported that coating increased the cracking, fracture and abrasion wear resistance in milling stainless steel at low speed. Therefore, coated tool had longer tool life than uncoated tool. Coating was also found to enhance the lubricity of the tool, improve the mechanical (such as mechanical cracking and fracture) and chemical wear resistance (such as oxidation and diffusion wear) and reduces cutting temperature and temperature variation of the tool, rendering it less susceptible to crack (Nordin *et al*., 2000; Arndt and Kacsich, 2003; Ghani *et al*., 2004; Liew and Ding, 2008).

The machining condition and wear mechanism are dependent on the cutting environment, cutting parameters, cutting tool and workpiece (Ema and Davies, 1989; Chung-Chen and Hong, 2002; Richetti *et al*., 2004; Korkut and Donertas, 2007; Tzeng, 2007). Hence, research is essential to determine the optimum cutting conditions. Recommendations from manufacturers should only be used as a guide because better cutting conditions for a specific situation can be only found through research (Richetti *et al*., 2004).

Ti-BASE HARD COATING, TiAlN AND TiCN

Titanium alloy are widely used owing to their low density, high specific strength, exceptional corrosion resistance and can stand high temperature. However, titanium alloys suffer from the serious disadvantages of poor tribological properties such as high friction coefficient, difficulty to lubricate and low adhesive and fretting wear resistance which prevent the applications of it as engineering tribological components (Yang *et al*., 2007). Various surface modification techniques have been

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proposed for the enhancement of its friction and impact resistant. The most recognized method consists of the formation of a thin layer of a hard ceramic phase, such as TiN and TIC, at the surface of cutting tool (Yang *et al*., 2007). The advantages of hard coating such as high hardness, lower friction coefficient and chemically stable had attracted the eyesight of the industry and the uses of hard coating was highly increased in the past 30 years (Chung-Chen and Hong, 2002). Ti-base coatings were widely applied to improve the lifetime and performance of a wide variety of tools.

TiN, TiC, TiCN and TiAlN and are the common used Ti-base hard coating. TiN possesses some very useful properties, despite its relatively lower hardness. It is chemically more stable and provides excellent resistance to the formation of BUE (Narasimhan *et al*., 1995). Despite of improving the tool wear resistance, the adhesive of TiN on the metal is poor due to the surface contaminants and residual tensions at the layer-metal interface (Yang *et al*., 2007).

Conventionally, a layer of TiN coating is often used to increase the surface hardness, reducing the coefficient of friction and to provide a layer of heat barrier to the cutting tool. The TiC coating has relatively higher affinity to the cemented carbide substrate compared to the TiN coating. TiC coating has greater propensity to develop the brittle eta phase at the interface and it has been suggested by many researchers that the formation of a small amount of eta phase is beneficial whereby it provides a diffusion interface to reduce the transfer of heat into the tool and leading to an improvement in adhesion (Narasimhan *et al*., 1995).

Titanium Carbonitride (TiCN) is the solidification of TiN and TiC. The inclusion of carbon atoms in the TiN lattice results in a substantial increase of the film hardness and in a lower friction coefficient. For these reasons Ti (C, N) coatings are often used in cutting tools and cold forming applications, replacing conventional TiN coatings (Bemporad *et al*., 2001). TiCN owns the excellence of both TiC and TiN. This has arisen from the fact that TiCN possesses high hardness and excellent wear resistance (Yang *et al*., 2007). Narasimhan *et al*. (1995) had found that TiN coatings had a larger crystallite size than the TiCN coatings and the adhesion property of TiN is better than TiCN. However, the microhardness of TiCN is higher than TiN, the coefficient of friction of TiCN is constantly lower than TiN and TiCN coatings can significantly reduces the cutting force compare to TiN coatings. Hence, TiCN coated cutting tool had better wear resistance and longer tool life than TiN coated cutting tool.

TiCN had chemical stability and superior mechanical properties such as low friction, high hardness (HV 2500-3000), high toughness, high melting point (3050°C), good electrical conductivity and excellent wear resistance (Narasimhan *et al*., 1995; Cheng *et al*., 2010; Yang *et al*., 2010). TiCN had better anti-wear capabilities compare to TiN and TiC (Narasimhan *et al*., 1995; Yang *et al*., 2010).

THE EFFECTS OF COATING DEPOSITION METHOD ON COATING PERFORMANCE

Physical Vapour Deposition (PVD) and Chemical Vapour Deposition (CVD) are the most common and conventional methods use to produce coating for cutting tool applications. The first cutting tool coating was produced by CVD in late 1960s and early '70s (Destefani, 2002). Generally, in CVD process, the tools are heated in a sealed reactor to about 1000°C (1830°F). Gaseous and volatile compounds supply the metallic and non-metallic constituents of the coating materials and inert gas is sometimes introduced into the reactor, depending on the needs. Thickness of CVD coatings can range from 5-20 μm. (Destefani, 2002).

PVD emerged in the 1980s as a viable process for applying hard coatings to cemented carbide cutting tools (Destefani, 2002) and is generally performed in vacuum chamber (Destefani, 2002; Suresha *et al*., 2006). The metallic sources of the coating, obtained via arc evaporation or sputtering, react with gaseous that provides non-metallic sources and subsequently produces thin films that deposited onto the substrate (Destefani, 2002; Suresha *et al*., 2006). Due to low pressure, the coating atoms and molecules undergo relatively few collisions on their way to the substrate. PVD is therefore a line-of-sight process that requires moving fixtures to ensure uniform coating deposition (Destefani, 2002).

The chief difference between PVD and CVD is the processing temperature. PVD process is carries out at a temperature much lower than CVD process, below 500°C, while CVD process is performs at a higher temperature of above 700°C (Hintermann, 1984; Nordin *et al*., 2000; Kopac *et al*., 2001; Destefani, 2002). The high temperature of CVD may changes or destroys the tribological properties of the substrate, increase the potential of catastrophic tool failure (Hintermann, 1984; Nordin *et al*., 2000; Kopac *et al*., 2001; Destefani, 2002; Yang *et al*., 2010) but enhances the adhesion of coating to the substrate (Hintermann, 1984; Destefani, 2002). For instance, Transverse Rupture Strength (TRS) of substrates decreased after CVD process or high temperature coating process but remained relatively unchanged after PVD process (Quinto *et al*., 1988). High temperature is needed to reach sufficient adhesion strength between coating and substrate (Yang *et al*., 2010).

The differences in deposition process condition resulted intrinsic microstructural differences between PVD and CVD coatings (Quinto *et al*., 1988). The grain and crystalline structure of PVD coating is very fine, resulted a very smooth and low coefficient of friction bright coating (Kopac *et al*., 2001; Destefani, 2002). The fine grain and crystalline structure of PVD coating enhances the diffusion wear resistance while CVD coating does not barrier to the diffusion wear (Kopac *et al*., 2001). However, CVD has the advantages of more uniform and homogeneous coating deposition (Hintermann, 1984). Smoother coating may adhere better to substrate (Destefani, 2002). One relatively new approach to dealing with coating roughness is post-coat mechanical polishing. The polished coating resulted smoother coating that has increase in lubricity and may adhere better to the substrate than untreated coating which is more susceptible to flaking (Destefani, 2002).

Among PVD, the sputtering PVD produced smoother and finer coating, while cathodic arc evaporation produced denser coating due to the higher proportion of ionized metal vapour. During arc evaporation, the bombardment of energetic metal ions may penetrated into substrate at angstrom levels and knock out some atoms, promoting the adhesivity of the coating to substrate (Suresha *et al*., 2006). Hence, the density and adhesivity of cathodic arc evaporation PVD coating are better than sputtering PVD coating (Suresha *et al*., 2006). Cathodic arc evaporation PVD process is also known as cathodic arc PVD (CAPVD).

PVD coating is essentially free of the thermal crack which is common in conventional CVD coating (Santhanam *et al*., 1996; Destefani, 2002). CVD coating is usually in residual tension stress at room temperature (Quinto *et al*., 1988; Santhanam *et al*., 1996; Selinder *et al*., 1998; Destefani, 2002), because coating material is generally have higher coefficient of thermal expansion than substrate (Destefani, 2002). The high residual tension stress may relieved by transverse cracks that don't affect coating adhesion but may initiate cracking and tool fracture (Destefani, 2002). High compressive stress that helps to resist crack initiation and propagation is developed in PVD coating (Quinto *et al*., 1988; Santhanam *et al*., 1996; Selinder *et al*., 1998; Destefani, 2002). Minimizing crack formation and propagation help in improving tool edge security and edge-chipping resistance, thus preventing premature tool failure (Quinto *et al*., 1988; Santhanam *et al*., 1996; Selinder *et al*., 1998; Destefani, 2002). Excessive stresses, however, causing poor adhesion and brittle behaviour of the coating (Selinder *et al*., 1998). Compressive stress can changes to tensile stress by annealing heat treatment (Quinto *et al*., 1988; Santhanam *et al*., 1996).

Other than thermal crack, high temperature CVD also results in formation of eta phase in substrate-coating interface, while eta phase formation is eliminated during PVD process (Santhanam *et al*., 1996; Destefani, 2002). Coupled with the formation of eta phase and high tendency of grown-in thermal crack, CVD-coated tool has lower edge fracture strength than PVD-coated tool, increase the tendency of edge chipping, particularly in interrupted machining when cyclic thermal and mechanical stresses were more influenced (Santhanam *et al*., 1996; Jindal *et al*., 1999; Destefani, 2002). This allowed PVD to coat on sharp edges and complex chip-breaker geometries tool, while in contrast, CVD-coated tools require an edge-honing or chamfer to strengthens its edge (Santhanam *et al*., 1996; Destefani, 2002). Therefore, comparison of the performance among coating shall takes the effects of tool geometries into account (Santhanam *et al*., 1996). Nevertheless, Narasimhan *et al*. (1995) has proved that their novel conventional CVD technique in TiCN coating production could controlled or even eliminated the formation of the brittle eta phase, despite it is often took place in conventional CVD process.

Although, it is recognised that the formation of brittle eta phases during coating deposition is harmful but some researchers has been suggested that the formation of a very small amount of eta phase during the formation of coating is beneficial, because it provides a diffusion interface that leading to an improvement of adhesion properties (Narasimhan *et al*., 1995).

CVD coatings are generally thicker than PVD coatings, on the order of microns thick versus as thin as a few nanometers. PVD is therefore often uses to produced multilayer coating (Destefani, 2002). Moreover, thinness PVD coating also enhance the ability to coat sharp edges (Destefani, 2002). The deposition of multilayer coating by PVD is more complex than single layer coating production which is usually involving the moving of the substrate or movable shutter to modulate the fluxes. Movable shutters involving complex engineering structures and thus are expensive. In some cases, interruption of the deposition by shutters may also lead to asymmetric deposition rate. Furthermore, modulation of fluxes using movable shutters involves the moving of shutters synchronously with evaporation from the sources. As result, it was difficult to obtain precise control of the coating properties as expected, especially when the layers are very thin (Suresha *et al*., 2006). It is more practical to produced superlattice coating by controlling the deposition fluxes, rotation and evaporating time. The substrates are placed between two targets and the revolving substrate is alternately exposed to each target, resulting in a layered thin film with periodicities that can be controlled by varying the rotation speed (Suresha *et al*., 2006).

Despite these multiple advantages brought by PVD process, CVD remains the dominant cutting tool coating process, especially in the United States. Some applications may require higher adhesion that produced by the chemical bond during CVD process. While PVD can deposit a wider range of coating materials on various substrates, there are some coatings and thin layers that can't be deposited using PVD process. For example, CVD is currently the sole method uses to produce diamond coating (Destefani, 2002).

Several researchers had reported that tribological properties of coating which includes composition and microstructure, are sensitive to deposition conditions and parameters (Navinsek *et al*., 1997; Kim *et al*., 2000; Bemporad *et al*., 2001; Destefani, 2002; Suresha *et al*., 2006; Yigit *et al*., 2008; Cheng *et al*., 2010). For instances, possibility of inter-layer slip can be resolved by varying deposition parameters (Bemporad *et al*., 2001), while adjusting process parameters in PVD allows modification from a columnar to an equiaxed microstructure (Destefani, 2002). Cheng *et al*. (2010) had reported that the growth orientation of the TiCN coating is strongly dependent on the deposition method.

During coating deposition by PVD that involves rotation, the composition of coating was significantly changes with small excursions in distance due to the planetary rotation. Moreover, the variances in the vapour pressure among coating components may causing composition inhomogeneity. Thus, coating with rich variety of composition and properties could be produced with this technique (Suresha *et al*., 2006).

In the production of thin crystalline layers by CVD, the probability of the adhesion is increased with temperature and thus leading to epitaxial growth. However, growth rate for CVD are too low to allow boule production, usually tens of micrometers per hour. The growth rate is increases with the temperature but this led to difficulty of controlling crystalline growth and problem of homogeneous nucleation in the gas phase may occur (Yigit *et al*., 2008).

Low deposition temperature not exceed 250°C should be used to PVD-coat CrN on alloyed tool steels and other heat sensitive substrate, because higher temperature will ruins the substrate (Navinsek *et al*., 1997). On the other hand, Kim *et al*. (2000) found that small changes in evaporation temperature had significantly affected the coating deposition. In the deposition of TiCN on aluminum alloy by metal-organic plasma-assisted CVD, the substrate was just partially coated at evaporator temperature below of 72°C and coating was spalled above 82°C. Good coating layers were obtained at temperature range of 74-78°C (Kim *et al*., 2000).

The concentration of gases and precursors used during coating deposition had significant effects to the tribological properties of coating and also the ease of process. Cheng *et al*. (2010) reported that concentration of mixture CH_4 and N_2 gases affected the composition, microstructure and subsequently properties of coating, in the production of TiCN coating by large area filtered arc deposition.

On the other hand, Kim *et al*. (2000) had found that chlorine from titanium precursor, $TiCl_4$, caused the deterioration of mechanical properties and increased the stresses induced in coating, when they produced TiCN coating by plasma assisted chemical vapour deposition process at temperature of approximately 450°C. They also had found that the ratio of hydrogen to nitrogen in chamber affected the hardness of the coating produced, where hardness was reduced with the increasing of nitrogen. Increased nitrogen content led to a bad dissociation of the precursor and thus more undissociated precursor molecules were incorporated in the layer and resulted low hardness (Kim *et al*., 2000). Mean while, Narasimhan *et al*. (1995) reported that in the CVD of TiCN coating, using organometallic precursor could reduces the deposition temperature to 800°C, as compared with 1000-1100°C in conventional CVD process and the formation of eta phases was reduced significantly (Narasimhan *et al*., 1995).

It can be derives that the deposition methods, coupled with the deposition conditions and parameters, had immense influences to the tribological properties and microstructure of the coating and also had non-negligible effects to the substrate and thus coated tool. Therefore, conditions and parameters during coating deposition process must be carefully controlled. Alternative deposition techniques which have high efficient, good consistency, more controllable, lower deposition temperature that prevents the damaging of the properties of substrate, are developed. These methods, for examples, are magnetron sputtering, laser technology and laser assisted deposition, cathodic arc evaporation and plasma assisted deposition. Unfortunately, all these alternative deposition methods also have its limitations and will not discuss in this study.

FACTORS AFFECTING THE COATING PROPERTIES

The properties of the coating can affect it performance which is strongly depend on the composition, stoichiometry, impurities, microstructure, imperfections and the preferred orientation (texture). The properties of the coating can be controlled during the process of the deposition of coating (Bunshah, 2001).

Microhardness of a coating plays an important role in the wear mechanism and higher microhardness will lead to higher wear resistance of the coating (Yang *et al*., 2010). In general, wear rate and wear mechanism strongly dependent on the microstructure and mechanical properties of the coatings and the characteristics of the impacting particles (Yang *et al*., 2010). In multilayer, microhardness was dependent on the bilayer period (Balaceanu *et al*., 2005).

The increasing of nitrogen contents will reduced the hardness and residual stress is increased with increasing of C/Ti ratio in the TiCN coatings (Kim *et al*., 2000; Cheng *et al*., 2010). The hardness is reduced because of the increasing number of undissociated precursor molecules which incorporated in the coating layer and resulting the reduction of hardness (Kim *et al*., 2000). Similarly, Narasimhan *et al*. (1995) had reported that the coarseness of the TiCN coating increased with the increasing of the contents of nitrogen in the film, mean while (Bemporad *et al*., 2001) had found that the hardness and friction properties of Ti (C, N) coating changes with the content of carbon (Bemporad *et al*., 2001).

Generally, TiCN lattice parameter values are located between the lattice parameter values of TiN and TiC. TiCN coatings is a solid solution of C atoms in TiN crystal lattice, the variation in the carbon content in the coatings causes significant changes in their crystalline and bonding structure. Internal stress and lattice parameter increases with increasing of C content in the TiCN coatings (Cheng *et al*., 2010). Since TiC and TiN are isomorphous, a TiCN coating can have a wide range of compositions, from carbon rich to nitrogen rich. Thus, TiCN lends itself eminently to the tailoring of composition and properties during deposition. The deposition of TiCN can be carried out on a wide range of substrates without greatly sacrificing the adhesion of the coating. A gradient of hardness can be achieved by controlling the C:N ratio in the TiCN coating layers. Properties and behaviour of the TiCN coating is a strong function of composition (Narasimhan *et al*., 1995; Cheng *et al*., 2010).

The sequences of the layer of coating had significantly effects to the mechanical and tribological properties of the coating. Surface properties such as wear resistance, hardness and coefficient of friction depend strongly on the properties of the outer layer of the film 20 (Narasimhan *et al*., 1995; Bemporad *et al*., 2001). Narasimhan *et al*. (1995) had improved the surface properties of the TiCN coating by providing a carbon-rich top layer to increase the hardness, wear resistance and surface smoothness of the coating (Narasimhan *et al*., 1995). Similarly, depositing TiCN coating as the surface layer in multilayer coating can improve the wear resistance significantly, this is due to the lower friction coefficient of TiCN compare to other Ti-base hard coating such as TiN and TiAlN (Hsieh *et al*., 1998; Chung-Chen and Hong, 2002).

Bemporad *et al*. (2001) had investigated the properties of multilayer TiN/TiCN coating. They found no noticeable interdiffusion is present but interlayer-slip has occurred, leading to the hypothesis that better bond may obtained when TiN is deposited on TiCN and not the contrary. To eliminate the interlayer-slipping with abrupt transition, they deposited a thin layer (some nm) between each TiN and TiCN film to obtain a graduated transition from the nitride to the carbon nitride and vice versa (Bemporad *et al*., 2001).

In this study, the most significant factor that affected the properties and performance of coating is unable to conclude but composition, thickness of coating, sequences of layers and deposition method are the major factors that influencing the properties and performance of coating and multilayer film.

PERFORMANCE OF COATING ON THE MACHINING PROCESS

TiAlN had the characteristics of high hardness, better wear resistance, chemical and thermal stability (Hsieh *et al*., 1998; Nordin *et al*., 2000; Ghani *et al*., 2004). When cutting with the TiAlN coated tool, a dense and highly adhesive protective Al_2O_3 surface film was found to form and prevent diffusion of oxygen into the tool. It was also found that considerably more heat was dissipated via chip removal. This allowed machining to be carried out at higher speeds without causing excessive thermal stresses on the substrate. However, the performance of TiAlN coating was less superior than TiN coating in low speed machining or interrupted cutting process due to its brittleness and high friction coefficient despite having better thermal stability (Ghani *et al*., 2004; Sokovic *et al*., 2004). Wear mechanism such as abrasion, attrition, chipping, plastic deformation and Built up Edge (BUE) were predominant when cutting cast iron at cutting speed 120-220 m min^{-1} using TiN coated tools (Siow *et al*., 2011). Jaharah *et al*. (2009) also found that good machined Surface was produced when end milling hardened steel using P10 TiN coated carbide tools. Wear mechanism and performance of PVD coated cemented carbides when milling of Ti-6Al-4V under dry condition was studied by Ahmad Yasir *et al.* (2008). They found attrition wear on flank and rake were the main cause of tool failure. Rapid tool wear was observed when the coating layer had been delaminated which explains that the chemical wear also contributes to the tool failure.

Yigit *et al.* (2008) had carried out an investigation on the performance of cemented carbide cutting tool coated with multilayer of TiCN+TiC+TiCN+Al_2O_3+TiN in dry turning of nodular cast iron. They had found that multilayer of TiCN+TiC+TiCN+Al_2O_3+TiN coated-cutting tool with 10.5 μm thickness of coating exhibited lower tool wear, had higher wear resistance, produced better surface finish and the cutting forces is lower compared to the multilayer of TiCN+TiC+TiCN+Al_2O_3+TiN coated-cutting tool with 7.5 μm thickness of coating. Their results shown that thickness of the coating had marginally effects on the performance of the cutting tool. Similarly, several researchers had found that the coating thickness of the multilayered coatings had significant effect on the wear resistance.

Sahin and Sur, (2004) studied the effect of Al_2O_3, TiN and Ti (C, N) based CVD coatings on tool wear in machining metal matrix composites. Flank wear increased with increased cutting speeds for all three tools. Kok (2010) studied the wear of cutting tools in the machining of 2024Al alloy composites reinforced with Al_2O_3 particles using varying sizes and volume fractions of particles up to 23.3 vol% by a turning process using TiN coated carbide tools and Ti+Ti(C, N)+TiN) coated carbide tools at different cutting speeds. The results show that the TiN coated tool sustains the least flank wear due to the extreme hardness and therefore high wear resistance of this material. Ti+Ti(C, N)+TiN) coated tools is found to be very unsatisfactory and sustains the most severe flank wear (Kok, 2010).

Jindal *et al.* (1999) had investigated the properties and performance of TiAlN, TiCN and TiN PVD-coated tungsten carbide tool. They had found that TiAlN coating had better adhesion properties than TiCN, where TiCN possessed higher residual stress that caused slips of the coating. Hardness evaluation showed that TiCN had the highest hardness among the coatings in room temperature but TiAlN had the highest hardness when the temperature exceeds 750°C. Both TiCN and TiAlN are harder than TiN in both range of temperature. In turning inconel, medium carbon steel (SAE 1045) and ductile cast iron under flood lubrication using these cutting tools, they discovered that TiAlN coated tool had the best wear resistance (crater wear and abrasive wear) and longer tool life, followed by TiCN and TiN coated tools and both TiAlN and TiCN coated tools were performed significantly better than TiN coated tool in all the tests. The better properties and performance of TiCN and TiAlN coated tool compared to TiN coated tool was partly attributed to the solid solution effect of either carbon or aluminum in the TiN lattice that strengthening the coating and increases the hardness of the coating. The formation of a stable Al_2O_3 layer on TiAlN coating endowed the TiAlN coated tool with higher resistance to abrasive wear and crater wear and makes TiAlN coated tools preformed better than TiCN coated tool and had longer tool life (Jindal *et al.*, 1999).

TiAlN had many advantages properties, i.e. high hardness at elevated temperature, low thermal conductivity and high thermal and chemical stability. Furthermore, TiAlN possessed high oxidation stability owing to the formation of a stable and protective Al_2O_3 film which in turn causes an improvement in the wear resistance of TiAlN coated cutting tool during machining process. The films also prevented intensive interaction between tool-workpiece and depressed the tendency of adherence of the workpiece material to tool surface (Fox-Rabinovich *et al.*, 2004). Fox-Rabinovich *et al.* (2004) had report that grain size refinement by using Filtered Arc Deposition (FAD) of TiAlN could accelerate the formation of alumina protective layer, leading to the improvement in oxidation wear resistance. This is a significant improvement especially in high speed machining when the oxidation wear is dominant. Additionally, finer grain size led to better surface finish that will further lowering the propensity of the adherence of workpiece material to tool surface and improved the chip flow (Fox-Rabinovich *et al.*, 2004).

TiAlN coating is better than TiN and TiCN coatings in high speed machining but suffers greater damage than TiN and TiCN in more mechanically influenced processes such as interrupted cutting or slow speed cutting. TiN tends to oxidize in temperature above 500°C and the formation of rutile phase TiO_2 which is brittle and poor in adherence ruined the protectability of the TiN coating and the formation of TiO_2 increases with increasing temperature. The oxidation of TiAlN led to the formation of Al_2O_3 which is a protective oxide layer that has high chemical stability that prevents diffusion wear, make TiAlN coating more superior in high speed machining. However, TiAlN coating is more brittle and had higher friction coefficient than TiN coating, this caused poorer performance of TiAlN coating in low speed and interrupted machining compare to TiN coating (Hsieh *et al.*, 1998).

Kim *et al.* (2000) had found that the hardness of TiAlN coating was higher than TiN coating. In sliding tests with alumina and steel balls, they had discovered

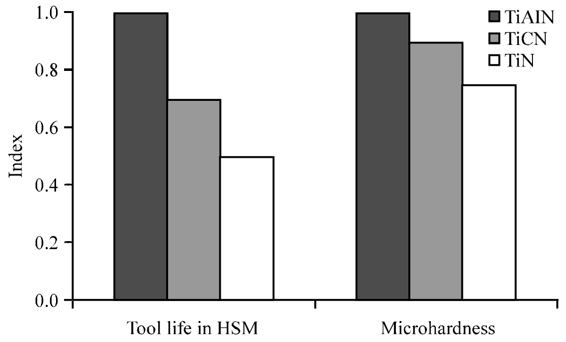

Fig. 1: Comparison among TiAlN, TiCN and TiN for tool life in high speed machining (HSM) and surface microhardness

that TiN coating had lower friction coefficient at lower sliding speed but higher than TiAlN coating when increasing the sliding speed to 0.5 m $\sec^{-1}$. This suggested that TiAlN is more superior than TiN in high speed machining (Kim *et al*., 2000). An index comparison had been plot (Fig. 1) to compare the tool life in High Speed Machining (HSM) and surface microhardness of TiAlN, TiCN and TiN.

Chung-Chen and Hong (2002) reported that TiCN and TiAlCN hard coating can improve tool life in the end milling of quenched AISI 1045 carbon steel. They found that TiCN coated tool had better tool life compared to TiAlCN coated tool. Chang *et al.* (2006) reported that multi component of TiAlCrN coatings synthesized by PVD exhibited better mechanical performance due to its advanced tribological properties and high temperature oxidation resistance. The incorporation of aluminum in the Face Centered Cubic (FCC) of TiN structure enhanced the coating thermal stability and hardness effectively. Hence, the oxidation resistance of the TiAlN coating can be further improved by the incorporation of chromium to form Cr based nitrides which are good in anti-corrosion. This could be the reason for the excellent performance shown by the AlTiCrN coated tool compared to the TiAlN coated tools in machining.

The advantageous of the Ti-base hard coating are strongly dependent in the cutting condition and some researchers are not satisfied with the performance of single/mono Ti-base hard coating, they thus combine two to three type of Ti-base hard coating become a Ti-base multilayer coating. For example, multilayer of TiCN/TiN coating can tremendously improve the wear resistance and properties of single TiCN and TiN coating. The duplex coating showed a marked reduction in the wear rate and cutting forces as compared with the single coating in the machining of 4150 steel, 1045 steel and nodular cast iron (Narasimhan *et al*., 1995).

Camuscu and Aslan (2005) had investigated different types of cutting tool performance in end milling of AISI D3 tool steel. They had found that TiCN/TiAlN coated carbide tool and TiAlN coated cermet tools exhibited similar performances in terms of tool life and surface finish, while TiCN coated carbide tool exhibited the worst performance. This also shows that TiAlN is a better coating material than TiCN for the machining applications of hardened tool steels. Ghani *et al.* (2004) found TiN coating perform better than uncoated tool when machining hardened steel at high cutting speed.

Yigit *et al.* (2008) had found that the TiN in multilayer of TiCN+TiC+TiCN+Al_2O_3+TiN coated cemented carbide tool made a consideration contribution to the tool wear resistance in dry turning of nodular cast iron. However, TiN in that multilayer coating had adverse effects on the quality of machined surface.

CONCLUSION

A thin film is deposited onto the surface of a cutting tool to improve the performance of the cutting tool. Ti-based hard coating is currently the most popular hard coating that applied in cutting tool application and is proved that can tremendously improve the performance and tool life of cutting tool, especially when machine difficult-to-cut materials. TiAlN coating is indeed performed better than TiN and TiCN coatings in high-speed machining but suffers greater damage than TiN and TiCN coatings in more mechanical influenced processes such as interrupted cutting and low-speed machining.

The performance of first and second generation of Ti-based hard coating is limited in certain cutting conditions. A new trend in developing Ti-based hard coating is toward tertiary Ti-based coating or high complexity Ti-based coatings like TiAlNbN and TiAlCN. On the other hand, some researchers combined two to three types of Ti-base hard coatings to form a new Ti-based multilayer coating, such as TiN/TiCN and TiCN/TiAlN. All these developments and researchers are aimed to improve performance of Ti-based hard coating.

It was found that the composition of the coating, thickness of the coating, sequences of the layer in multilayer coating and the coating deposition methods can affect the properties of the coating and hence the performance.

There are researchers reported that Ti in Ti-based coating was oxidised during high temperature machining. Thus, other elements are searched to replace Ti. These elements, for examples, are Cr and Zr that forming CrN and ZrN, aiming to further improve the performance of coating. However, the superiority of CrN and ZrN to TiN is yet to conclude.

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