A

Seminar Report

On

"Introduction to TiAlN Coating"

Submitted by

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C E R T I F I C A T E

This is to certify that the Seminar Report entitled,

"Introduction to TiAlN Coating"

has been submitted by

Hanwante Sarang R

as a partial fulfillment for the Bachelor Degree in
Production Engineering

Prof. B R Kharde
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DEPARTMENT OF PRODUCTION ENGINEERING
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C E R T I F I C A T E

This is to certify that

Hanwante Sarang R

Student of B.E. (Production Engineering) was examined in the Seminar entitled

"Introduction to TiAlN Coating"

on /12/2002 at

Amrutvahini College of Engineering
Sangamner.

INTERNAL EXAMINER **EXTERNAL EXAMINER**

Acknowledgement

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Abstract

With the demands of lower cost, higher accuracy, better surface finish, and shorter process time in the precision engineering industry, high-speed machining of high-hardness materials including hardened tool steels has become increasingly important. To improve the performance and to extend the life of the cutting tools, various types of hard coatings have been developed. Hard coatings for high-speed machining consist of multiple layers because of the requirements for high-adhesion strength to the substrate, high-thermal stability, high hardness, a low-friction coefficient, and good compatibility. The present techniques used to produce these coatings include physical-vapor deposition, such as sputtering and ion plating, and plasma-enhanced chemical vapor deposition. Traditionally used coatings like TiN, CrN, and their alloyed nitride coatings, have high hardness and good adhesion strength on common materials used in the tooling industry. However, these coatings have poor performance in high-speed machining applications, especially in the cutting of hardened tool steels, because of phase transition (oxidation) at high temperatures. One of the most promising systems for this application is ***Ti–Al alloyed ceramic (nitride and/or carbide) i.e. Titanium Aluminum Nitride (TiAlN)****, which has high-thermal stability, a low-friction coefficient, and high hardness. Much work has been done worldwide to develop and commercialize this coating for high-speed cutting and milling tools.*

Contents

1. INTRODUCTION

1.1 Tool Wear

As a result of load factors exerted on the cutting edge during machining, a few basic wear mechanisms dominate metal cutting:

1. abrasion wear
2. diffusion wear
3. oxidation wear
4. fatigue wear (static or dynamic)
5. adhesion wear

The tool material's ability to resist the loads determines how it will be affected by the wear mechanisms of metal cutting. Abrasion wear is caused mainly, but not entirely, by the hard particles of the work piece material. This is similar to a grinding operation where the hard particles come between the surface of the work piece and tool. The mechanical load on the insert leads to wear on the flat face of the cutting-edge flank.

To a large extent, the cutting edge's ability to resist abrasive wear is connected to its hardness. A tool material densely packed with the hardest of particles will stand up well to abrasive wear, but it may not be equipped to cope with other load factors during machining.

Diffusion wear is more affected by the chemical load during the cutting process. The chemical properties of the tool material and the affinity of the tool material to the work piece determine the development of the diffusion-wear mechanism. Hardness of the tool material doesn't affect the process very much. The metallurgical relationship between the materials determines the extent of the wear mechanism. Some cutting tool materials are inert against many work piece materials, while others have high affinities.

Tungsten carbide and steel have affinity toward each other that creates a diffusion-wear mechanism. This wear forms a crater on the insert's chip face. Because this mechanism is very temperature dependent, it's more pronounced at higher cutting speeds. Atomic interchange occurs with a two-way transfer of ferrite from the steel into the tool, as well as carbon diffusing into the chip.

In the presence of air, high temperatures produce oxidation wear in most metals. Tungsten and cobalt form porous oxide films that the chip rubs off more easily. But when

stronger and harder oxides are produced (such as aluminum oxide), certain cutting-tool materials may be more susceptible to oxidation wear. This is especially true with regard to the interface portion of the cutting edge where the chip width finishes (at the depth of cut). At this point, air gains access to the cutting process and oxidation can create notches in the edge. This form of wear, however, is relatively uncommon in today's machining.

Fatigue wear is often a thermo-mechanical phenomenon. Fluctuations in temperature and loading forces can crack or break cutting edges. Intermittent cutting action leads to temperature cycling that creates shocks at the point where the cutting edge engages the work piece. Some tool materials are more sensitive than others to the fatigue mechanism. Pure mechanical failure can result from cutting forces that exceed the cutting edge's mechanical strength. This can be caused by hard or strong work piece materials, high feed rates, or when the tool material isn't hard enough. Usually, however, plastic deformation is the principal form of fatigue wear.

Adhesion wear (also known as attrition wear) occurs mainly at low machining temperatures on the tool's chip face. This can affect long-chipping and short-chipping work piece materials including steel, aluminum and cast iron. This mechanism often forms a built-up edge (BUE) between the chip and the cutting edge. In this process, successive layers from the chip are welded and hardened, becoming part of the edge.

As machining continues, the BUE may shear off by itself or cause the tool's cutting edge to break away (either in small pieces or by fracturing). Some cutting tool materials and work pieces (for example, very ductile steel) are more susceptible to this pressure-welding than others. At higher cutting temperatures, however, the conditions that produce this phenomenon usually do not exist. An adhesion-wear mechanism represents a combination of a specific temperature range, affinity between the tool and work piece materials, as well as the load from cutting forces. When machining deformation-hardening materials (for example, austenitic stainless steel) this wear mechanism produces rapid local wear at the maximum limit of cutting depth. This is the most common type of notch wear, and it depends on the affinity between the tool and work piece materials.

This tool wear can be minimized by means of suitable coating on tools which makes tool within the cutting forces and to sustain its properties and giving out no effect on productivity. There are number of tool coatings available in market like TiN, TiC, and TiAlN etc.

2. TOOL COATINGS

2.1 Properties of Cutting Tool Materials:

Following are some important properties, which should be kept in mind while selecting the coating material. Due to lack of these properties coating is made on the substrate tool material.

1. **High Wear Resistance:** It is necessary to enable the cutting tool to retain its shape and cutting efficiency.
2. **Hot Hardness:** It is necessary to enable the cutting tool to retain its cutting ability and hardness at elevated temperatures.
3. **Sufficient Toughness:** It is necessary for the cutting tool to withstand the forces, to absorb shocks associated with interrupted cuts and to prevent the chipping of the fine cutting edge.
4. **Adequate Strength:** To withstand cutting forces.
5. **Dimensional Stability:** Tool material should be able to retain dimensions during cutting operations.

2.2 Necessity of Coatings:

Though many developments in the cutting tool materials and surface treatments are carried out, not a single material have a fruitful combination of all those properties required by a machining process. In order to have longer tool lives and increase in productivity, one must go for surface engineering on tools.

The harder materials lack in toughness and also they are sensitive to vibration and chatter. The refractory materials possess excellent wear resistant material on a tougher substrate.

The coatings are extremely fined grained and dense with a high degree of purity. As the coatings are diffused into the underlying metal, the bond is perfect. The coating becomes a part of the tool. Low thermal conductivity properties also eliminate cold welding and chip building-up. Thus a coating possesses excellent combination of above mentioned properties.

The performance of coated and uncoated tools can be predicted with the help of Fig.1 which is a graph of tool wear Vs time plotted under same machining conditions.

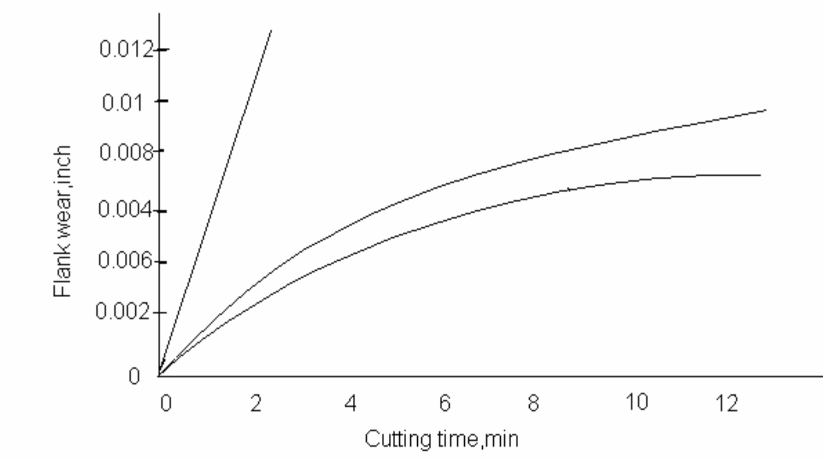
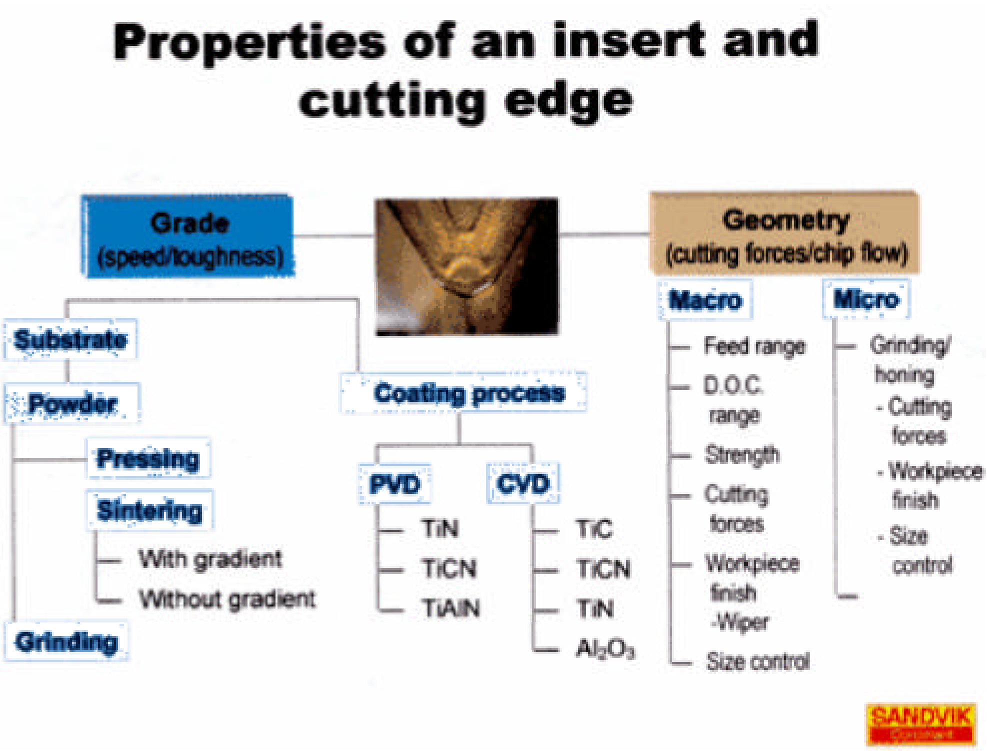
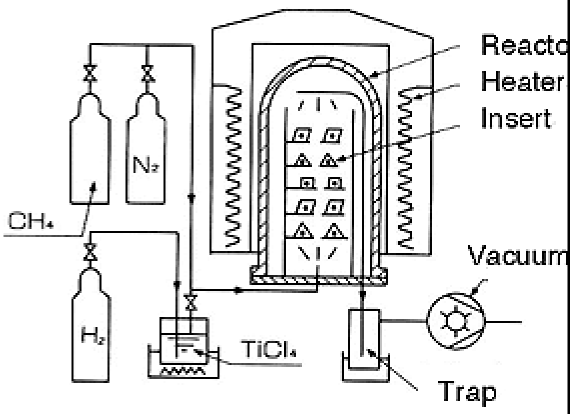
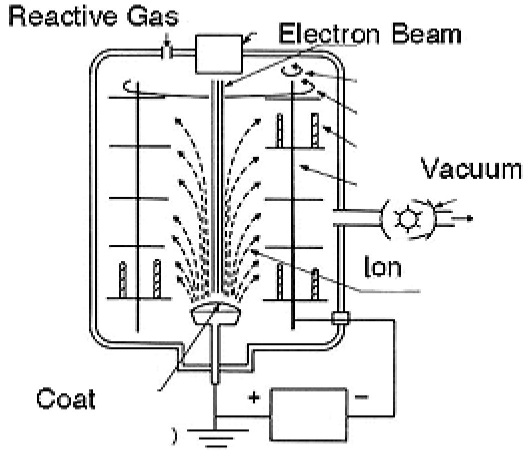


Fig 1: Tool wear Vs time for coated and uncoated cemented carbide tool tips. Uncoated steel cutting grade, coated WC-Co alloy, coated steel cutting grade.



2.3 Types of Coatings:

CVD	PVD
	
1. Equal Coating for all surface. 2. Suitable for Mass Production. 3. Substrate's Bending Strength decreases. 4. Substrate may deteriorate. 5. Substrate may soften.	1. Not Suitable for Mass Production. 2. Substrate's Bending Strength does not decrease. 3. No Substrate's deterioration. 4. Good for Anti-Chipping Performance.
Coating Temp. 900 (1100 U C	Coating Temp. 400 (600 U C
Coating Thickness 6 to 9 µm	Coating Thickness 1 to 3 µm
e.g. TiC, TiCN, TiN, Al_2O_3	e.g. TiN, TiCN, TiAlN

For PVD coating, there is no formation of eta phase, and it is possible to maintain the sharpness of the cutting edge. Applications of PVD are in Drilling, Reaming, Milling, Gear Cutting., etc.

The prominent advantages of PVD coating: Low coefficient of friction, High Adhesion, Smooth Surface, Edge radii need not be altered, and that Coating can be "stripped" by a patented Balzer process.

The advantage of the coating is due to the high hardness of the coating, which is drastically higher than the original material (substrate). The hardness of different coatings is very much higher than the hardness of the basic tool materials, and therefore the capabilities of High Parameters, & Long Life.

Basic Tool Materials (Hardness in VPN)	Coatings (Hardness in VPN)
HSS: 720 VPN	TiN: 2250 VPN
Hard Metal: 1400 VPN	TiCN: 3000 VPN
	FUTURA(TiAlN): 3500 VPN

Other advantages of hard coating on tools are: Chip flows smoothly; No Built-up Edge; Very useful on Low alloy Steels, Tool Steels, and Stainless Steel.

The heat generated at the cutting edge – how it affects: In HSS tools, the heat distribution is quick and high. In 5 seconds, the temperature rises to 90^{o} C, and in 10 seconds it reaches the level of 120 ^{o} C. With Coating, the temperature does not rise above 47^{o} C)

It was clear that the chip formation with coated tools is cleaner, and chances of welding or Built-Up Edge are removed. Due to the edge retention, these advantages of chip formation are available over a long period.

3. TiAlN PROPERTIES

3.1 Standard Coating Application Chart

		EDP First Digit	Hardness	Thermal Stability
TiN	Titanium Nitride	2	2900HV	500C (950F)
TiCN	Titanium Carbonitride	4	4000HV	400C (750F)
AlTiN	Aluminum Titanium Nitride	5	4500HV	800C (1450F)

3.2 GRADES & ADVANTAGES OF PVD COAT INSERT

Grade	Color	Coat Film	Application	Advantage
PR510	Gold	TiCN + TiN	Milling of Gray Cast Iron and Nodular Cast Iron	High Wear Resistance
PR610	Gold	TiN	Turning of Free Cutting Steel Turning of Gray Cast Iron and Nodular Cast Iron	High Wear Resistance
PR630	Gold	TiN	Milling of Steel Grooving, Threading	High Wear Resistance High Toughness, Excellent Surface
PR660	Gold	TiN	Stainless Steel Milling of Steel	Anti-Welding Performance Anti-Chipping Performance
PR730	Gold	TiAlN + TiN	Milling of Steel	High Wear Resistance Anti-Welding Performance Anti-Chipping Performance
PR905	Bluish	TiAlN	High Speed Machining of Free	Excellent Stability at High Temperature

	Purple		Cutting Stainless Steel	Smooth Tool Surface High Wear Resistance and Plastic Deformation Resistance

3.3 Comparison Chart

Coating	**TiN**	**ZrN**	**AlTiN**	**TiCN**	**CrN**	**Solid Lubricant**	**Amorphous Carbon**
Coating Designation	7-22	7-40	7-13T	7-22C	7-24	MoST©	Tetra Bond®
Hardness	2900 +- 200	2800 +- 200	4500 +- 500	4000 +- 400	2500 +- 400	2000	8000
Adhesion	70	70	70/80	62	70	90	80
Oxidation Temperature (Fahrenheit)	950	1100	1450	750	1300	850	950
Coefficient of Friction	0.65	0.60	0.42	0.45	0.55	0.01	0.10
Surface Roughness	0.2	0.2	0.15	0.18	0.2	0.02	0.02
Ductility (%)	1.09	1.00	1.2/1.5	0.2/0.3	NA	NA	NA
Color*	Gold	Gold	Black	Silver	Silver	Silver	Black

* Colour shade vary from industry to industry

3.4 TiAlN coating gave big advantage even over TiN.

As an example of TiAlN advantage over Tin, Operation: Punching / Forming

- Uncoated: 5000 Strokes
- TiN Coated: 10,000 Strokes
- TiAlN Coated: 20,000 Strokes

Constant research was going to see how best the heat can be carried away by the chip. Thus came the development of BALINIT **FUTURA – Titanium Aluminium Nitride.** This is very useful in Dry Machining; and has excellent resistance to Oxidation. Almost concurrently, the development of BALINIT **X TREME** - **Multi Layer Coatings** came through.

In FORMULA 1 racing cars, the gears are coated with BALINIT HARDLUBE (TiAlN), Balinit FUTURA and Balinit XTREME are both product of TiAlN Coating.

For PVD Coating, there are two processes: IONITRON TECHNIQUE and ARC TECHNIQUE. The IONITRON technique uses Electron Beam melting of Titanium under High vacuum to give Very Smooth, Shiny, Adherent film without droplets. Titanium and Nitrogen are bombarded onto the tool. This process is Microprocessor Controlled, and Individual Control of Coating Parameters makes it possible to mix tools in one batch. The following schematic figure gives us an idea about the process.

The major advantages are Extended Tool Life Time, Reduction of Machine Downtime, Reduction of Maintenance Costs, consistently Good Quality of Parts Coming Out, Suppression of Lubrication, Less Rejected Pieces and Smooth, Dent free, Wrinkle free Pressed Parts. He cited the example of a French car manufacturer who was using 21,000 Tons of Lubricant for dies every year. With the use of Coated Dies and Punches, this consumption reduced to 82 Tons / Year.

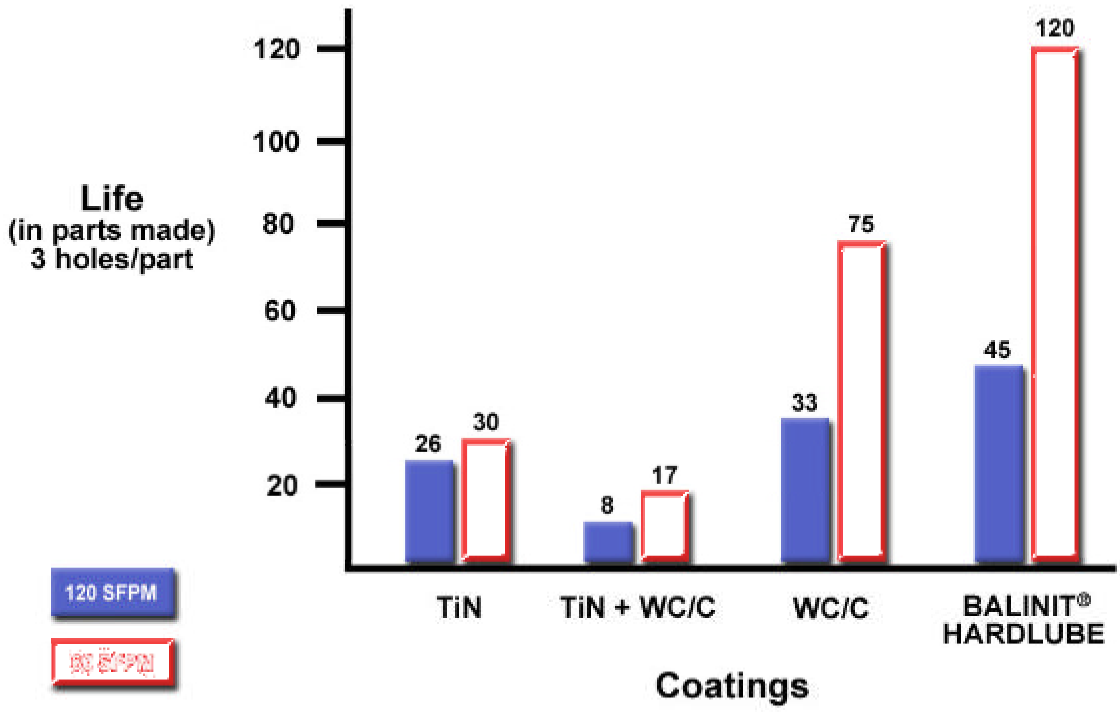
The figure below gives guidance for selecting the proper coating for proper applications.

Balinit A TiN | Balinit B TiCN | Balinit FUTURA | Balinit X TREME

High Demands (Hard, Dry, HSC)

Normal Demands (Wet, Standard Cutting Conditions)

HSS | Hard Metal



4. SCOPE OF TiAlN COATED TOOL.

4.1 Machining tools

Worked material	Excellent	Fine	Satisfactory
High-alloyed steel, low alloy steel and stainless steel at medium and high cutting speeds	TiAlN	TiCN	TiN
High-alloyed steel, low alloy steel and stainless steel at low cutting speeds, e.g. HSS milling cutters	TiCN	TiAlN	TiN
Cast iron	TiAlN	TiCN	TiN
Al and AlSi alloys, cast aluminum	TiAlN	TiCN	CrN
Cu and Cu alloys, brass, bronze, aluminum bronze, nickel silver, Ti and Ti alloys	CrN	TiAlN	TiCN
Ni and Ni alloys, hard alloys, Hastelloy, Inconel	TiAlN	TiCN	
Plastics	TiAlN	CrN	TiCN
Graphite, green compact, plastics with filler	(diamond)		TiAlN

4.2 Tools for punching, forming and pressing

Worked material	Excellent	Fine	Satisfactory
High and low alloy steel plate and sheet, stainless steel plate and sheet	TiCN	TiAlN	TiN
Al and Al alloys	CrN	TiAlN	TiCN
Ti and Ti alloys, Cu and Cu alloys	CrN	TiAlN	TiCN
Ni alloys, precious metals, gold, platinum	TiAlN	TiCN	
Plastics, plastics with filler, glass, sintering powder	TiAlN	CrN	TiCN

5. ADVANTAGES OF TiAlN COATING ON TOOLS

- Longer Tool Life
- Faster Machining Rates
- Fewer Re-sharpening.
- Fewer Setups
- Higher Productivity
- Better Part Finish
- Dry Machining
- Fast Payback on Initial Coating Investment

According to **Balzers India Limited** there are many advantageous features of TiAlN Coating as;

1. **Improve yields and productivity:** Coated tool lasts for longer period time. Moreover coated tools enables use of higher parameters.
2. **Reduce machine Downtime:** Coating acts as a wear indicator; tools change frequency can now be calculated and planned. Resulting in minimized tool breakage caused by fatigue and overuse.
3. **Cut Manufacturing Stages:** Coated tools allow higher degrees of metal deformation enabling reduction of manufacturing stages. Also cleaning efforts is considerably reduced as components with finer surface and with minimal coolant are produced.
4. **Reduced Costly and time consuming finishing operation:** Coated tools stay in shape longer and produce top-notch ready to install components with finer surfaces, tighter manufacturing tolerances and better dimensional accuracy. This is important particularly for work-pieces that need to look perfect.
5. **Conserve consumables:** The option for environmentally friendlier production range from smaller lubricant quantities to dry production, as coated tools reduce friction, generates less heat and moreover as coatings sustain high temperature encountered during process. Cleaning can even be eliminated entirely in dry processes – a must in food and pharmaceutical applications.
6. **Be Eco-Friendly:** With coated tools you use less and work with ecologically safer lubricants. This not only reduces the effort and cost involved in re-conditioning but also makes your Eco-balance look good.

7. **Cost across the board:** Less is more – particularly in context of tool wear. TiAlN Coatings makes a tangible contribution to cost savings in several respects resulting in greater cost effectiveness.
8. **Cut tooling costs:** As coated tools results in less wear and lasts longer, enable more re- grinds.
9. **Cuts manufacturing costs:** With improved productivity, reduced machine downtime and higher cycle frequencies. Fewer tool failures also reduces load on tool maintenance.
10. **Cut Cost of quality:** With reduced inspection cost due to reliability process control coated tools invariably produce top-notch ready to install components with finer surfaces, tighter manufacturing tolerances and better dimensional accuracy. Also coated tool reduce rejection and generates less scrap.
11. **Cut expenses on consumables:** Coated tools ensure reliable separation of tool and work-piece even under adverse lubrication condition avoiding seizure resulting in significantly reduces cost of coolant \ lubricants.

6. CASE STUDY

6.1. INTRODUCTION

This Case Study reports the development of a multilayered (Ti, Al, N) Ceramic hard coating for high-speed machining tools using an unbalanced magnetron-sputtering system. The process parameter dependence of the coating properties was studied and discussed. High-speed-milling field testing on hardened tool steel was also investigated.

6.2. EXPERIMENTS

Coatings were deposited on WC substrates using a Teer 550 unbalanced magnetron-sputtering system.5, 6 Figure 1 shows a schematic diagram of the deposition chamber. Two pairs of rectangular Al and Ti targets were installed around a cylindrical vacuum chamber. High-purity argon and nitrogen were used as the discharge and reactive gases. The coating composition was controlled by the sputtering power applied to each target, and an optical,

TABLE I. Basic deposition conditions for Al–Ti ceramic coatings.

Base pressure (Torr)	1.5×10^{-5}
Plasma cleaning	Biased at dc 980 V for 30 min
Deposition pressure (mTorr)	7–7.5
Power for Ti target	dc 2.8 kW
Power for Al target	1.2–2.1 kW
Substrate bias (V)	60–130
Substrate temperature (°C)	~300
N_2 partial pressure (mTorr)	0.5–1
Film thickness (μm)	2–3

Emission monitor was used to monitor the poisoning status of the target surface. The basic deposition conditions are tabulated in Table I. Figure 2 shows the coating design concept. The coating starts with a Ti bond layer, followed by a TiN interlayer, then gradually increases the Al content to form a graded Ti–Al–N transition layer, and finishes with an Al–Ti–N top layer. Ti has good bonding strength with WC and high-speed steel materials. This, together with the TiN transition layer, ensures good adhesion strength of

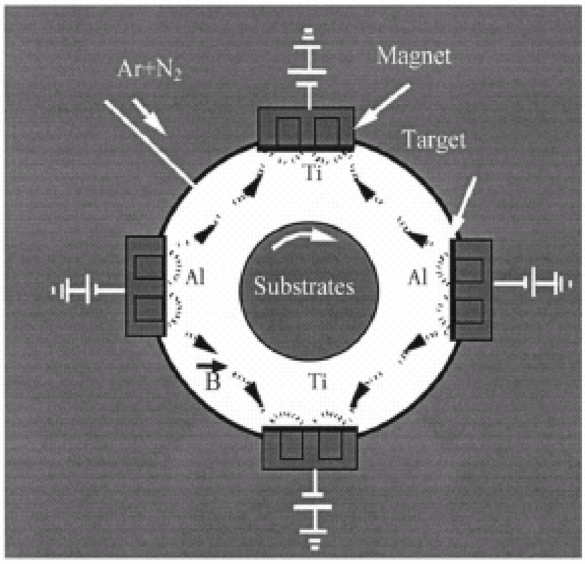


FIG. 1. Schematical diagram of the unbalanced magnetron-sputtering deposition system.

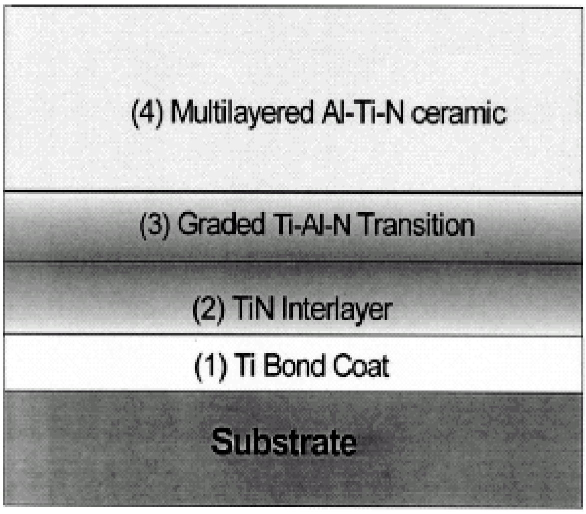


FIG. 2. Design concept of the Al–Ti–N coating. In layer (3), the relative content of Al:Ti was increased from 0 to 1:1.

the coating to the substrate. The top layer was processed as a multilayered structure to achieve both high hardness and low residual stress, and also high-oxidation resistance by alternatively depositing the Al-rich layer and Ti-rich layer, and also by using different plasma bombardments on the growing film surface. The coating crystal structure was analyzed by x-ray diffractometry (XRD) Using Cu *K* a x rays. The surface morpholo gy and cross sections of the coatings were studied by scanning electron microscopy. For some samples, x-ray photoelectron spectroscopy (XPS) (VG Escalab 2201-XL) Was used to measure the coating composition. To evaluate the micro hardness and the adhesion strength, nano-indentation and scratch tests were carried out. Optical microscopy was used to confirm the starting point of the scratch failure. For field testing of the coating performance, two fluted f6 mm micro grain WC ball-nose end mills were selected as the test tools. The WC grain size is about 0.8 mm. A MIKRON HSM700 high-speed machining center was used for the milling experiments. The material used for the milling tests is AISI 420 tool steel hardened to HRC52. Table II tabulates the milling field test conditions and the main material properties.

TABLE II. Milling field test conditions and the properties of work material.

Cutting speed (m/min)	260
Depth of cut (mm)	0.2
Coolant	Air mist
Composition of the work material:	C: 0.38, Mn: 0.5, Cr: 13.6, V: 0.3
Hardened steel	Fe: balance
Rockwell hardness	HRC 52

During the tests, the flank wear of the end mills was inspected and measured at an interval of every 5 m of machining using a Leica microscope with IMAGE database software. The magnification used was 503. The maximum flank wear *Vb*8 was recorded and analyzed. The tool life criterion is *Vb*850.3 mm. The total cutting distance before reaching this criterion was used to quantify the performance of the coating and the tool life of the tested end mill. At the end of each test, the milled surface roughness of the specimen was measured using a Taylor–Hobson's stylus profilometer.

6.3. RESULTS AND DISCUSSIONS

A. Structure and composition

Figure 3 shows a typical XRD spectrum of the AlTiN coating. The coating has a polycrystalline structure with preferential growth. Depending on the substrate bias, the ratio of the relative intensity of the XRD peak At 2 u; 37° at 2 u; 43° varied from 0.5 to 5, which strongly affect the mechanical properties of the coating (to be discussed later) On the other hand, the composition and the relative content of Al to Ti are critical to the mechanical properties and oxidation resistance of the coatings, as evidenced by the adhesion, hardness, and oxidation temperature measurements. Stoichiometry or near stoichiometry is necessary to achieve high hardness and good adhesion strength. Increasing Al content can obviously increase the oxidation resistance, due to the formation of a dense Al_2O_3 layer on the surface of the coating. However, this reduces the hardness of the coating from 35–40 to 20–25 GPa. Another problem is that the Al- rich layer has low bonding strength with the base layer, regardless of whether it is pure metallic Ti, or ceramic TiN, resulting in poor adhesion of the coating. For this reason, a compositional grading process is necessary. Therefore, we deposited an Al–TiN transition layer on the TiN base layer, then a low-Al AlTiN support layer, followed by a high-Al top layer. The transition layer starts with an Al content of 0, and gradually increases to Al: Ti; 1:1.5–2, the preset composition of the low-Al Al–Ti–N layer. The high-Al AlTiN layer has two designs, corresponding to two compositions: Al: Ti; 1:1 and 2:1. The milling field tests show that the second design, i.e., Al: Ti; 2:1 shows better performance, due to its better thermal stability. As an example, Fig. 4 shows the XPS spectrum obtained from the coating surface, and Fig. 5 shows the depth profiles of the atomic concentration in the top layer and the low-Al TiAlN sub layer. As designed, the top layer of the coating has a concentration of l: Ti: N; 1:1:1.8, a near-stoichiometric composition, and the sub layer has a concentration of Al: Ti: N; 1:1.5:1.7. This combination provides the coating with good mechanical properties.

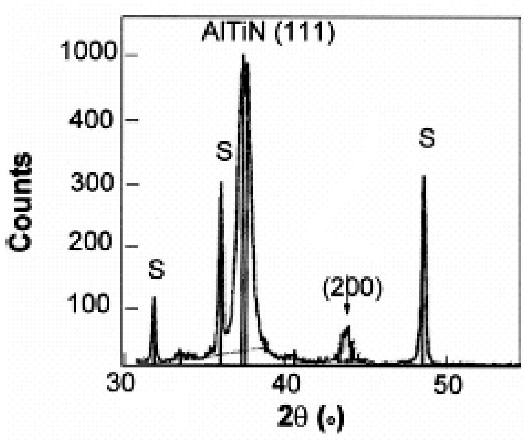


FIG. 3. XRD spectrum of AlTiN coating deposited under the substrate bias of 80 V. The peaks labeled with *s* are from the substrate diffraction.

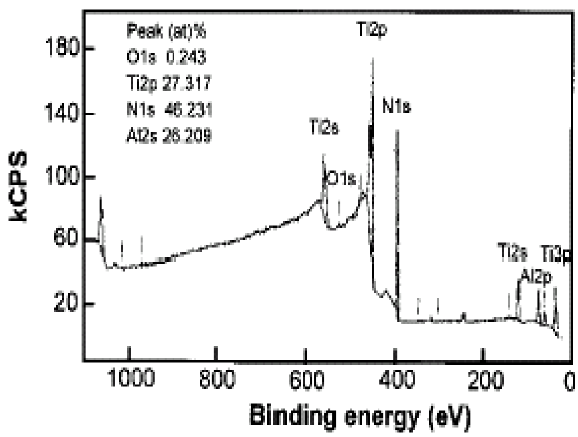


FIG. 4. XPS spectrum of AlTiN coating, obtained from the surface layer.

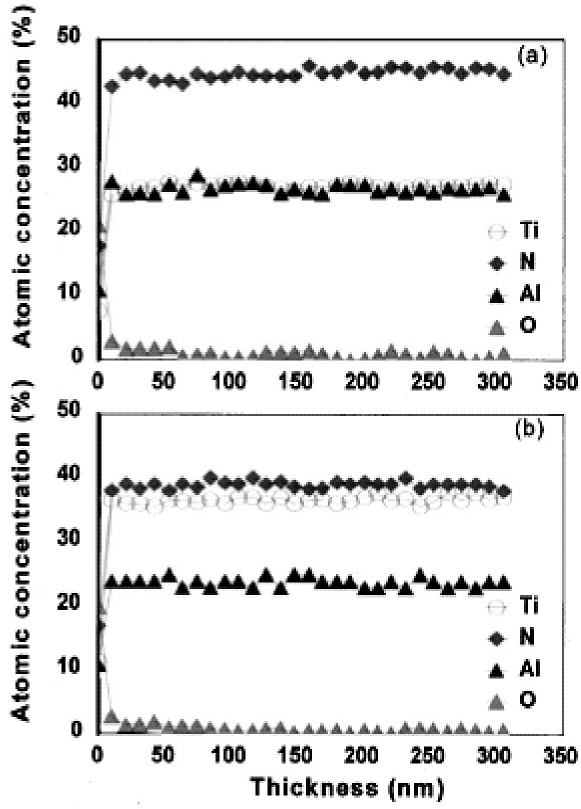


FIG. 5. Depth profiles of the atomic concentration in the (a) top layer and (b) low-Al AlTiN sublayer.

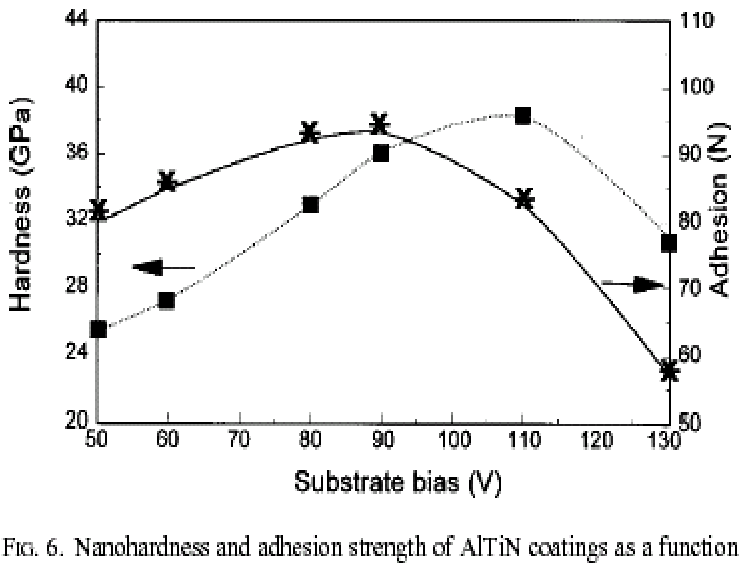


FIG. 6. Nanohardness and adhesion strength of AlTiN coatings as a function of substrate bias.

B. Hardness and adhesion

The main process parameters determining the mechanical properties of the coating include substrate bias power, sputtering power, and discharge and reactive gas flow rates.10–13 Sputtering power and the reactive gas flow rates determine the composition of the coating. Provided the coating has a stoichiometric composition, the substrate bias, which provides effective ion bombardment on the substrate surface, is the most critical parameter to determine the crystalline structure, hardness, and adhesion. In this work, the dc bias from 50 to 130 V was tested. Figure 6 shows the bias dependence of the hardness and adhesion strength. With the increase of the bias power, the hardness increased substantially, and the adhesion strength first increased and then decreased in the range of 50–110 V, due to the increase in ion bombardment. Further increasing the bias power resulted in highly stressed films which cracked in some cases, and the adhesion strength substantially decreased. Therefore, reducing the internal stress without sacrificing the hardness is a key point to obtain good-quality coating.

C. High-speed-milling field testing

A total of nine cutters that are identical in geometry and tool material were field tested at a cutting speed of 260 m/min. Two of them were uncoated, two commercially TiAlN coated, and five graded AlTiN coated in this work. Setting the flank wear *Vb*850.3 mm as the end-of-life indicator, the cutting distance of all nine testing end mills were recorded. The results are shown in Table III. Apparently, all coated tools showed much improved tool life compared to the uncoated ones. All five cutters coated in this work have longer tool life when compared with the commercial ones. The best one, cutter No. 1, has a tool life of 93 m, which is about 4.7 times that of the uncoated end mill.

TABLE III. Milling field test results.

Cutters	Cutting distance (m)	Surface roughness (R_a, μm)
Uncoated Nos. 1 and 2	20	~0.4
Commercial TiAlN	52	~0.4
Coated Nos. 1 and 2		
Coated in this work:		
No. 1	93	0.26
Nos. 2 and 3	80	~0.32
Nos. 4 and 5	65	~0.38

Besides the good mechanical properties achieved in this coating, the unique thermal properties, which include oxidation resistance and heat insulation, play a critical role in this performance. Here, heat insulation or low thermal conductivity of AlTiN protects the cutting edge by insulating the tool substrate from damaging high temperatures and by dissipating the heat to the machining chips. The surface finish of the work material is another important end-mill performance indicator. High smoothness or low roughness is required in many applications such as mold and die machining. Also tabulated in Table III is the comparison of the surface roughness (*Ra*) achieved using the above end mills. Cutter No. 1 coated in this work shows the best surface finish with *Ra*; 0.26 mm, compared with 0.40 mm of the uncoated and commercial TiAlN-coated cutters. This surface finish satisfies the requirements for most applications in the precision machining industry.

6.4. SUMMARY

A multilayered TiAlN coating was developed for high-speed machining tools. The coating shows good mechanical and thermal properties. High-speed-milling field testing shows that the tool life with these coatings is improved by a factor of 4 compared to the uncoated tools. The surface finish achieved with our coated tools is also significantly better.

7. CONCLUSION

TiAlN *is the most recently developed coating with a hardness of 3300 HV and is temperature resistant up to 800°C i.e. Excellent Stability at High Temperature and Smooth Tool Surface, Balanced Wear Resistance and Fracture Resistance, allowing the use of ultra high-speed machining operations. This multi-purpose coating is also suitable for working cast-iron, High Speed Turning of Stainless Steel and Al alloys and reduces friction and adhesion of plastics materials to the moulds. New applications are found every day with this very efficient, high productivity tool.*

The cutting tool must be chosen not just for its wear resistance, but also for its ability to retain this wear resistance at higher temperatures. TiAlN protects the tool by acting as a thermal barrier in case of High speed machining or high temperature machining. The coating is about 35% more heat resistant than titanium nitride (TiN).

The couple of previous industrial test results on Structure and composition, Hardness and adhesion, High-speed-milling field testing indicates that dry machining using TiAlN is now a probability, not just a possibility, with a wide range of industrial applications possible for general machinery and components.

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