International Journal of Applied Engineering Research ISSN 0973-4562 Volume 13, Number 14 (2018) pp. 11653-11664

Coatings of Cutting Tools and Their Contribution to Improve Mechanical Properties: A Brief Review

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Abstract

Cutting is an important process in the manufacturing industry. It is necessary to use good quality cutting tools in order to maintain the quality of a product. The coating on a cutting tool has a great impact in terms of the mechanical and tribological properties as well as the end results of the product. A cutting tool can made of various types of materials, but the most commonly used material in the industry today is cemented tungsten carbide as its characteristics meet the requirements of manufacturers. To improve the performance of cutting tools, various coatings have been applied to the tools, among them being single coatings, multi-layered coatings, nanocomposites and superlattices. Hierarchical-structured coatings are the latest discovery in the manufacturing industry. This review discusses cutting tools, their functions and coatings as well as their hierarchical structure in order to assist researchers in understanding the appropriate coating structure for cutting tool applications.

Keywords: Cutting Tools, Hierarchical Coating, Nano indentation

INTRODUCTION

The cutting process involves the removal of material from a workpiece to produce a specific design. The quality of the cutting process is assessed in terms of the end result of the product and the lifetime of the cutting tool itself. Cutting tools are made of various types of materials including cemented tungsten carbide, high-speed steel, diamond and boron nitride. All these materials have their own mechanical and tribological properties, but cemented tungsten carbide is the most commonly used material in the industry, especially for steel cutting applications. This is because cemented tungsten carbide is reasonably priced and has a high level of hardness and boiling point. However, the performance of a cutting tool does not depend on the material alone.

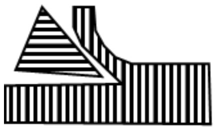
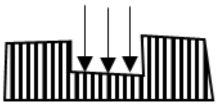
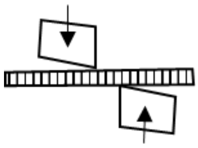
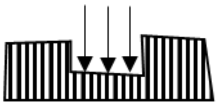
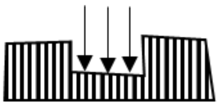
The performance of a cutting tool can be improved by applying a coating to the surface of the cutting tool. Various types of coating structures and materials can be combined to produce high-performance cutting tools. The coating not only functions to extend the lifetime of the cutting tool but it also acts as a protection against wear, especially against abrasions and adhesions, in cutting tool applications. The strength of the coating is dependent on the material used for the coating, but studies have shown that a more layered structure will further enhance the hardness of the coating and increase its resistance to wear. Currently, a combination of various materials such as TiALN/TiN, TiCN/TiSiN/TiAlN and many more are being used for multi-layered coatings. These multi-layered combinations will produce distinctive mechanical and tribological properties.

A recent study on the structure of coatings was carried out by [1], through the introduction of a multi-layered hierarchical coating. This coating consists of 2 or more coating materials arranged according to a hierarchical structure, with different individual thicknesses. According to this study, such a structure can increase the wear resistance of a coating and protect the material from crack propagation.

CUTTING TOOLS IN INDUSTRIES

The cutting process is a core process that involves various other processes in the manufacturing industry [2]. The cutting process can be defined as a mechanical manufacturing process where a part is formed by removing or separating out a material that is known as the chips until the desired shape is obtained [2]. The unnecessary part will be removed by shear deformation. What is important about the material or tool in the cutting process is that the type of work material should always be harder than the material that is to be processed [2]. This basic fact is very important because it will determine the quality of the final product. Table 1 shows the cutting categories that are being used in today's industry. These processes are familiar to product manufacturers in the industry.

Table 1. Type and example of machining process that involve cutting

Category of Basic properties	**Fundamental Removal Method**	**Example of Processes**
Mechanical	I 	Cutting Milling Drilling Grinding, etc.
	II 	Water Jet Cutting Abrasive Jet Machining Sand Blasting etc. Ultrasonic Machining
	III 	Blanking Punching Shearing
	IV 	
Thermal	II 	Thermal Cutting Electron Beam Machining Laser Machining
	III 	Electrodischarge Machining (EDM)
Chemical	II 	Etching Thermal Cutting
	III 	Electrochemical Machining (ECM)

To produce a product with a good and neat end result, several requirements need to be emphasized in determining the type of cutting material to be used. The cutting process involves direct contact between the cutting material and the workpiece. Therefore, the cutting material will be exposed to a high mechanical load and heat during the cutting process. The requirements for the selection of a cutting material are very important and have been summarized in the following list [2, 3, 4, 5]:

a) High strength at high temperatures
b) High compressive strength
c) High bending strength
d) High deformation resistance
e) High fracture strength
f) High fatigue resistance
g) Heat resistance
h) Expected wear characteristics
i) Adequate lubrication
j) High stiffness
k) Low chemical bonding or high chemical stability.

For the selection of cutting materials, as in Figure 1, studies in 2013 have shown that cemented carbide has a dispersion of 53%, while high-speed steel has a dispersion of 20% [6].

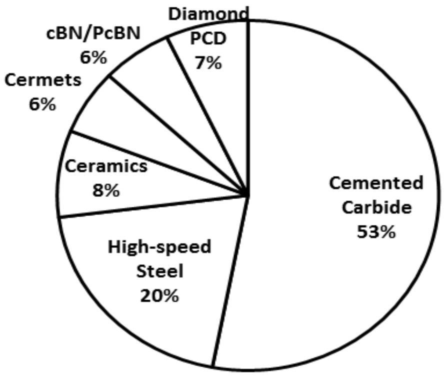


Figure 1. Market distribution of cutting tool material on the year 2013

Changes to and the identification of workpieces, manufacturing processes as well as new regulations by the authorities have motivated the advancement of cutting tools. For maximum productivity, industrial machine operators need to produce at the fastest rate with minimum manufacturing costs. For this purpose, cutting tool manufacturers as well as researchers have been constantly on the lookout for the optimum mix of materials, coatings and geometries for cutting tools [7].

Table 2. Cutting tool material list

Material	Young's Modulus, E (Gpa)	Hardness (HV)	Compression Strength (MPa)	Heat Conductivity ($Wm^{-1o}C^{-1}$)	Electric Durability (μΩ cm)
WC	625-700	2200-3600	3350-6830	55-80	20-100
Diamond	1220	10000	9000	2000	1e19-1e22
WC-CO	400-650	700-2200	3000-9000	70-120	16-20
Steel	150-200	240-300	250-1760	15-65	15-120
SiC	400-460	2300-2600	1000-4500	80-130	1e9-1e12
Al_2O_3	343-390	1200-2060	500-2700	26-38.5	1e20-1e22

The earliest record of the use of cutting materials is that of steel hardened by heat or the alloying of elements [2]. With the increasingly rapid development of technology, steel cutting tools are rarely used and have been replaced by materials that possess better mechanical properties and that provide savings in terms of costs and energy. The rising demand for cutting tool materials is the result of measurements taken to promote productivity and as well as the sustainability of machining processes such as the minimum quality of the lubricant, high cutting speed and performance, and hard machining [6]. Table 2 is a list of cutting tool materials provided by cutting tool manufacturers. The mechanical and tribological properties indicate the performance of the cutting tools. The types of materials shown are those that are frequently and commonly used in the machining industry.

TYPES OF COATINGS FOR CUTTING TOOLS

Layers can be produced in various shapes and structures by using different combinations of materials [8]. The number of layers can be single coatings, multiple coatings and various other types [9].

a) Single Coating

A classic PVD layer such as TiN, Ti-C-N, CrN, Ti-Al-N is based on a single-coating architecture. This architecture has different characteristics in terms of its structure, morphology, composition, gradient, grain size and defects, which are influenced by the processing parameters, that have an impact on the characteristics of the coating [10]. The incorporation of additional elements can revive the ability of a single layer to improve the machining performance.

b) Multiple Layers

A multi-layered coating is made up of a lamellae structure of 2 or more materials that are uniformly layered [10]. The advantages of using a multi-layered coating are that it is able to adapt to pressure, it promotes adhesion to the substrate and improves the resistance to crack propagation [11]. The multi-functional design of the coating, which depends on the cross-layering system, can be realised by fulfilling the requirements for cutting applications such as adjusting to the desired composition and thickness of the coating. It is expected that by adjusting the composition and controlling the thickness of each layer, the requirements of the cutting application can be met.

c) Superlattices

Nano-scale multi-layered coatings, known as superlattices, have been developed to enhance the hardness and strength of a system. A key element in the concept of superlattices is the very thin layer measuring less than 10 nm, which is said to be able to prevent the formation of dislocations, while the difference in the elastic modulus between the layers will impede the mobility of the dislocations. The weakness of superlattices is that the effect of the nano layers in the superlattices can be lost if the resultant layers do not follow the correct order [10].

d) Nanocomposites

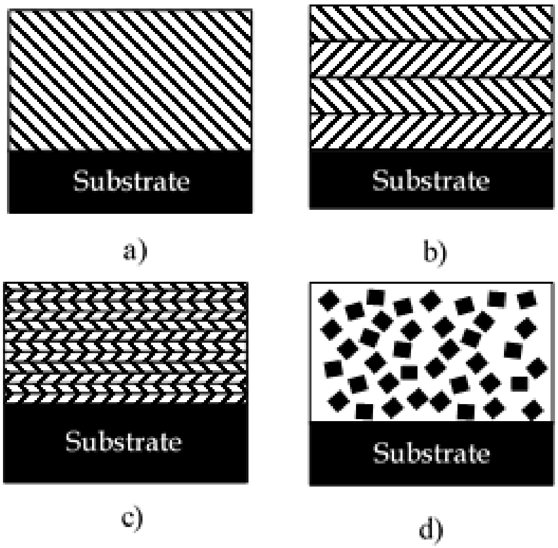


Figure 2. Schematic diagram type of coatings that used in cutting tools a) Monolayer b) Multilayer c) Superlattices d) Nanocomposites

Nanocomposite layers are derived from at least 2 phases that cannot be implemented together or in combination, namely, 2 nanocrystalline (nc/nc) phases, or the more common, single nanocrystalline and single amorphous phase (nc/a). Various hard compounds can be used in the nanocrystalline phase, including nitrides, carbides, borides, oxides and silicon. The percentage volume and dispersion of the nanocrystals should be optimized to obtain a compromise between hardness and strength [10].

The single coating or mono-phase micro-layered structure displays better tribological results if compared to the bulk material. However, the coating is technically unsuitable when it comes to energy efficiency for cutting tool applications [11]. The efficiency resulting from 2 layers can be improved further by introducing an intermediate layer between the upper layer and lower layer [12]. With the introduction of such a layer, the multi-layered structure can extend the lifetime of the cutting tool more effectively than a single coating.

THE ROLE OF COATINGS IN CUTTING TOOLS

Most recent studies have explored the features of multi-layered coatings with mechanical properties such as fragility, plasticity and resistance to abrasive wear, and theories and models have been designed to predict those properties [9]. From the start, the main focus for the development of coatings has been as a protection against abrasive and adhesive wear [6]. In continuous cutting, the coating will ensure that surface contact conditions are optimal to reduce alignment pressure in the wedge cutter and to improve the stability of the shape. In addition, the coating should have a high residual compression pressure level to ensure a high direct compression pressure during the cutting process. The coating must also adhere well to the surface of the cutting tool, where this will extend the lifetime of the cutting tool until the coating on the surface of the platform vanishes completely [12].

Figure 3. Schematic diagram of 3 layers coating

A triple-layered coating was introduced, as shown in Figure 3, where each layer has its own function, as follows [9]:

1. A wear-resistant outer layer

   This layer is in direct contact with the material that is to be processed, and its main function is to reduce the physical and chemical activities of the cutting tool material and to reduce adhesion to the workpiece.

2. Intermediate layer (transition)

   The main function of this layer is to support the work capacity of the wear-resistant layer and the absorption of the strong adhesion the wear-resistant and adhesive layers.

3. Layer of adhesive sublayers

   This layer is in direct contact with the cutting tool material, and its main function is to provide a strong adhesion between the cutting tool material and the coating.

Figure 4 shows a schematic diagram of the structure of a multi-layered coating produced with layers that have different functions and purposes, while Figure 5 presents a view through an electron microscope of a multi-layered coating with a repetitive dual-layered structure.

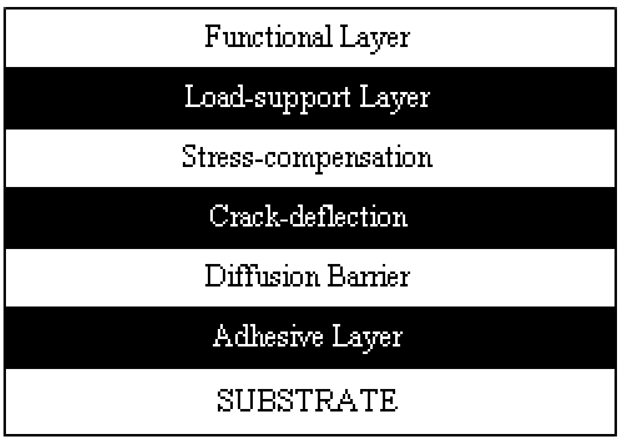


Figure 4. Multilayer coating and functions

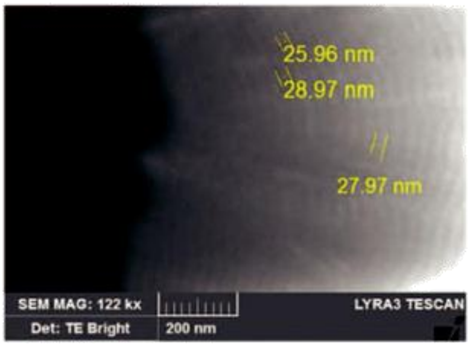


Figure 5. Multilayer view

The coatings were analysed and measured according to several criteria to ensure the use of a coating that functions optimally to reduce wear and friction, increase the lifetime of the cutting tool and the machining quality. Table 3 shows the analysis of the criteria for the coatings that are usually used for cutting tool applications and which can be found in the market. Table 4 shows the types of coating materials that are the choice of cutting tool manufacturers.

Table 3. Coating mechanical properties

Type of Coating	**Hardness (GPa)**	**Hardness ($HV_{0.05}$)**	**Thickness (μm)**	**Friction Coeficient**	**Heat Stability (°C)**
TiN	23	2350	1 - 4	0.4	500
TiCN	27	2750	1 - 4	0.2	450
CrN	21	2100	1 - 4	0.6	700
TiAlN	32	3300	1 - 4	0.5	600
TiAlCN	29	3000	1 - 4	0.4	500

Table 4. Coating material function

Type of Coating	**Functions of the Coating**	**Reference**
TiC	Excellent abrasive wear resistance	[3]
TiN	Reduces friction and prevents adhesive wear and BUE formation	[15, 16]
Ti(C,N)	High fracture strength and excellent abrasive wear resistance	[3]
TiAlN	Displays high thermal hardness, ductility and thermal impact resistance	[3, 16]
Al2O3	Excellent thermal separation, and good oxidation resistance	[3]
CrN	Excellent wear and corrosion resistance, low friction and internal pressure resistance	[17]

CEMENTED TUNGSTEN CARBIDE AS SUBSTRATE

Carbide was introduced to the European market around the years 1920 to 1923 as a material that has a combination of characteristics such as high hardness, crack strength and wear resistance [13]. Such relevant characteristics have made cemented carbide the main material of choice for cutting and drilling tools, mining bits and wear-resistant components in various industrial applications [14].

Cemented carbide is one of a group of compounds including nitrides, borides and silicates in the table of scales. Carbide is an important tool material in this group, with dominant functions being displayed by tungsten monocarbide, WC. Table 5 shows the melting point temperature and hardness at room temperature of several types of carbides. In that table, it can be seen that all the values shown are much higher compared to steel, although carbides are not as hard as diamond [14].

Table 5. Carbide properties

Carbides	Melting Point (°C)	Diamond Hardness Indentetion (HV)
TiC	3200	3200
V4C3	2800	2500
TbC	3500	2400
TaC	3900	1800
WC	2750	2100

The carbide variants that are used most commonly are tungsten carbide (WC), titanium carbide (TiC), tantalum carbide (TaC), and niobium carbide (NbC). Most of the binders used are cobalt (Co) binders because studies have found that cobalt is the most efficient material for binding carbide to metals. The percentage of hard particles in carbide tools can be varied and changed at a rate of approximately 60% to 90%. By adjusting the type, size and concentration of the particles, manufacturers can produce the appropriate material properties to meet the requirements of various applications [3].

Cemented tungsten carbide has been used extensively in the hard metal industry for the production of cutting tools, drill bits and others. Table 6 shows the chemical composition of cemented tungsten carbide for cutting tool applications.

Table 6. Chemical composition in cemented tungsten carbide

Element	Weight (%)
W	81.23
C	5.2
Co	10.15
Fe	0.98
Al	0.062
Ti	0.005
Mo	0.0007

WC-CO has a high hardness due to the ability of cobalt to remove tungsten. The small size of the tungsten carbide grains, measuring approximately less than 0.1 µm, enables them to have a high surplus strength [2]. In addition, the WC-CO tool can withstand a high load in the process and allows a high cutting speed. Therefore, this tool is often used to process materials that are difficult to cut such as titanium [13]. The remarkable performance shown by WC-CO in various tribological conditions is due to a combination of the high hardness of the tungsten carbide particles, the high fracture density of the Co binder and strong inter-phase adhesion.

Depending on the cutting conditions, the workpiece and the tool material, the performance shown by the cutting tool is confined to the wear at the nose, the wear at the edges, wear of the craters, the debris at the end or a combination thereof [18]. Briefly, in the context of a cutting tool, wear can be defined as the loss or dislocation of weight of a material due to a tribological phenomenon. From the data obtained, there are 2 mechanisms that may occur with the cemented tungsten carbide coated cutting tool, namely [9]:

1. A stable wear mechanism with the main wear being on the surface of the edges. The wear that occurs on the edges of the cutting tool is either deformed or insignificant and only affects the outside of the coating.
2. A wear mechanism that will cause an intensification of wear with an extremely high risk of wear on the tool being disastrous. A high degree of crater wear occurs on the surface of the tool, with partial destruction of the coating surface.

CEMENTED TUNGSTEN CARBIDE COATING

The technology for the deposition of a thin film coating on a substrate material can generally be categorized into two types, namely, chemical vapour deposition (CVD) and physical vapour deposition (PVD). Physical vapour deposition (PVD) is a type of vacuum coating process, where the material used will be physically separated from the source by evaporation or sputtering. After that, it will be transported by the vapour energy of the particles and will condense on the material to be coated by forming a thin film. Chemical compounds can be deposited using the same source material. This process can also be carried out via reactive gases such as nitrogen, oxygen or simple hydrocarbons containing the desired reactant materials, where these gases will act with the target metals. On the other hand, chemical vapour deposition is a thermal-activated process, where the substrate material will be heated and will then react with a chemical gas compound. The major reactive vapours are metal halides, metal carbonyls, hydride compounds and organometallic compounds. To break down the metal compound, the substrate material will usually be heated to a relatively high temperature [19].

Table 7. Wear explanations in cutting tools

Wear mechanism	Factors that cause wear	Characteristics required for cutting tools to handle the problem of wear	References
Abrasive wear	Hard particles on the workpiece remove the cutting tool material by means of a ploughing action.	High matrix hardness, high hard phase volume, hard coating.	[20]
Light and severe adhesive wear	High-speed cutting results in a high temperature on the tool surface, thereby causing adhesion between the workpiece and the tool material. The situation becomes severe with machining of a workpiece that is pliable, ductile, chemically active and with low conductivity.	Smooth tool surface, sharp edges, good hardness and temperature, high thermal conductivity and chemically-glazed coating.	[20, 21]
Plastic deformation	High-speed cutting results in high temperature at the edges of the tool and a high load.	Good hardness at high temperatures, high thermal conductivity.	[22]
Fracture and fatigue	Intermittent cutting with a combination of a high cutting speed as well as the use of a cutting fluid, high pliability of the workpiece, the use of a cutting tool with edges that are not sharp enough.	Smooth tool surface, high fracture pliability of tool material with fine grains on the matrix and high hardness phase.	[22, 23]

CVD technology was commercialised several years ago but it is PVD technology that is clearly having an impact in the market [24]. PVD technology is successful because it enables the deposition process to be conducted at a lower temperature of 450-550 °C compared to the CVD process, which is conducted at a temperature of 550-1100 °C. This development in PVD technology facilitates the deposition of a thin film coating on the CTC because the deposition temperature is below the softening temperature of high-speed steel [25]. In addition, the advantage of PVD is that it can precisely control the thickness of the coating, especially on the edges of the cutting tool. This enables the production of a cutting tool with sharper edges [26]. A compressive stress will be generated through the PVD process [27]. This feature can prevent cracks in the cutting edge when exposed to a strong impact [26].

As revealed in the study by [19], cutting tool materials should have three main characteristics, namely, a high level of hardness, good fracture pliability and chemical stability. It is almost impossible to find all three characteristics in a substrate material without a coating, and in fact, they can hardly be found in cutting tools with a single coating. Therefore, multi-layered coatings are applied to overcome this constraint. Multi-layered thin film coatings incorporate the desired characteristics of different materials to produce a cutting tool material that is suitable for certain cutting applications. Examples of such applications include the use of interface binding layers to increase the adhesive strength and inert thin coatings on wear-resistant coatings to prevent [28]. According to [29], multi-layered TiAIN thin films that can be found in the notes are TiAlN/TiAlCN, TiAlN/TiNbN, TiAlN/TiN, AlN/TiN/TiAlN, TiAlN/CrN, TiAlN/Mo, and WC/TiAlN. They also found that almost all these multi-layered coatings display characteristics that are better than those of single-layered coatings. The advantages of multi-layered coatings are:

a) Avoid micro-debris and pull-outs from the material during machining operations.
b) Reduction of adhesive wear due to the nano-crystalline structure compared to the sinusoidal structure in thick single-layered coatings.
c) Individual components in conventional PVD coatings are transformed plastically when subjected to mechanical loads and will result in a rough suspension and crack propagation in a perpendicular direction. On the other hand, a smooth suspension occurs on the surface of a multi-layered coating with no obvious evidence of plastic deformation and crack propagation.

Mechanical Properties of Single Cemented Tungsten Carbide Coatings

Many studies have been carried out by researchers on various types of cemented tungsten carbide coatings using a variety of deposition techniques. The mechanical properties of these coatings, such as the hardness and Young's modulus, are shown in greater detail in Table 8.

Table 8. Hardness and Young's modulus thin films of a single coating based on substrate, deposition and thickness from different research studies.

Substrate	Coating	Deposition Technique	Thickness (μm)	Hardness (HV)	Hardness (GPa)	Young's Modulus (GPa)	References
WC-CO	TiAlN	PVD	-	-	-	-	[30]
WC-CO	TiAlN	PVD	5	2964 ± 380	-	-	[31]
WC-CO	Ti (C, N, O)	PVD	-	-	-	-	[32]
WC-CO	TiCN	PVD	-	-	-	-	[33]
WC-CO	TiAlN	PVD	-	-	-	-	[34]
WC-CO	TiN	PVD	-	-	-	-	[35]
WC-CO	CrAlSiN	CVD	-	-	33 ± 1	-	[16]
WC-CO	TiAlSiN	CVD	-	-	31 ± 2	-	[16]
WC-CO	TiAlN	CVD	-	-	19 ± 2	-	[16]
HSS	AlCrN AlCrSiN	CVD	-	-	-	-	[36]
WC-CO	TiN	PVD	4.0	3073 ± 216	-	398 ± 18	[15]
WC-CO	TiAlN	PVD	3.9	3133 ± 130	-	350 ± 11	[15]
WC-CO	TiAlN	PVD	-	-	29.42	550	[37]
WC-CO	TiAlN	PVD	-	2478.32 ± 87.530	26.76 ± 0.944	523.45 ± 41.018	[38]
WC-CO	AlCrN	PVD	-	2914.04 ± 257.740	31.26 ± 2.782	469.99 ± 75.914	[38]

Mechanical Properties of Multilayers Cemented Tungsten Carbide Coating

For multi-layered coatings, most of the researchers used 2 to 3 types of combinations of materials for the layers. These types of materials were able to contribute to the mechanical and tribological properties of the coating and had a bearing on the performance of the coating in the cutting process. It could be seen that the multi-layered coating was more effective in terms of the hardness and Young's modulus compared to the single coating. This was seen, for example, in the study by [39] into the characteristics of both types of coatings, namely, a single coating and multi-layered coating, where WC-CO was used as the substrate, while TiAlN/AlCrN was the coating material. In that study, it was clearly stated that the multi-layered coating was more efficient in terms of its mechanical properties. The hardness of the multi-layered TiAlN/AlCrN coating in the study was 32.75 GPa, while the hardness of the single coatings of TiAlN and AlCrN was 26.76 GPa and 31.26G GPa, respectively. The same could be said of the Young's modulus, where the multi-layered coating had a higher value than the single coating. Table 9 shows the values of the mechanical properties that were studied by previous researchers using various types of materials in the multi-layered coatings of cemented tungsten carbide with different deposition techniques.

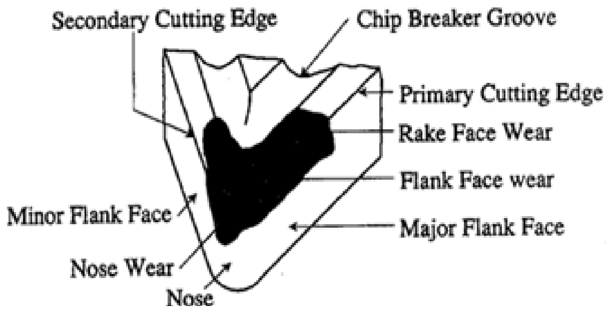


Figure 6. Wear pattern and term

Table 9. Hardness and Young's modulus thin films of a multilayer coating based on substrate, deposition and thickness from different research studies.

Substrate	Coating	Deposition Technique	Thickness (μm)	Hardness (HV)	Hardness (GPa)	Young's Modulus (GPa)	References
WC-CO	Ti-TiCN-TiAl (C, N)	FCVAD	5.5	-	37	-	[9]
WC-CO	Ti-TiCN-TiAlCr (C, N)	FCVAD	3.8	-	39	-	[9]
WC-CO	Ti-TiN	FCVAD	4.0	-	29	-	[9]
Co-Cr	TiN/CrN	PVD	-	-	-	-	[41]
WC-CO	TiN/TiAlN	PVD	3.2	2996 ± 150	-	369 ± 15	[15]
WC-CO	TiAlSiN/TiSiN/TiAlN	PVD	3.6	3240 ± 363	-	309 ± 18	[15]
WC-CO	TiAlN/AlCrN	PVD	-	3033.015 ± 292.126	32.75 ± 2.614	561.97 ± 57.620	[38]
WC-CO	TiN/TiAlN	-	8	-	-	-	[23]
WC-CO	Al_2O_3/TiC	-	-	-	21.5 ± 0.5	-	[41]
WC-CO	TiCN/TiC	PVD	6	1888 ± 225	-	-	[31]
WC-CO	Al_2O_3/TiC	PVD	6	1633 ± 150	-	-	[31]
WC-CO	TiCN/Al_2O_3/TiN	CVD	-	-	-	-	[42]
WC-CO	Al_2O_3/TiCN	CVD	-	-	-	-	[43]

MULTI-LAYERED HIERARCHICAL STRUCTURE

Over the last decade, many studies have been carried out on multi-layered coatings in the search to continuously improve the hardness and adhesion of the coating in response to contact with a mechanical tool. The main function of the coating is to prevent the occurrence of dislocations between the surfaces of the layers and different types of materials and to prevent crack propagation in the film coating [1]. However, significant changes in the mechanical properties will result in a decrease in the binding strength between the layers, thereby leading to fragility. However, if a precise transition is replaced by a continuous transition such as a hierarchy or a slope in the structure of the multi-layered coating, the binding strength can be improved [39].

The hierarchical structure contains a multi-layered coating between 2 or more materials, but each layer has a different thickness. With different numbers of layers and thickness of the coating, this hierarchical structure shows very encouraging results in terms of the wear rate and strength of the coating compared to a single coating or a common multi-layered coating.

So far, there has not been any recent study on hierarchical coatings, especially for cutting tool applications. In 2016, only [1] produced research findings on the effectiveness of a hierarchical structure using a WC/WCN/W type of coating and comparing it to a non-coated CoCrMo substrate.

They studied the mechanical and tribological properties of the hierarchical structure. The structure of the study carried out by him, together with the schematic diagram of the layers and the substrate can be seen in Figure 7. The hierarchical structure that was used was of 2 types, namely, a HIGH and LOW hierarchy, where the variation used was the thickness of the individual layers.

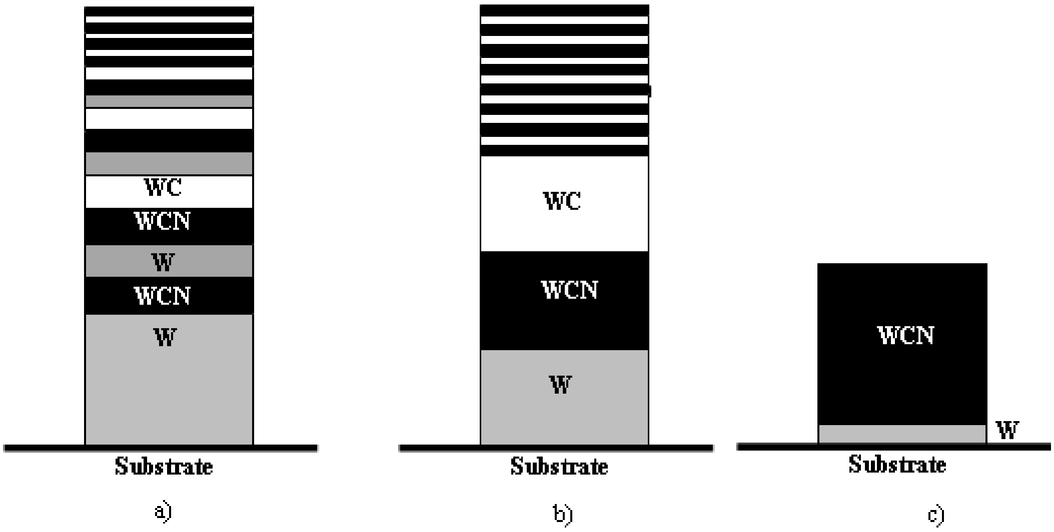


Figure 7. Schematic diagram of a) HIGH Hierarchy coating b) LOW Hierarchy coating c) WCN Monolayer

Contribution of Hierarchical Coating to Coefficient Of Friction

Figure 8 and Table 10 show the coefficient of friction values for all the experimental samples. Based on the figure, both hierarchical structures indicated a more stable μ with values of ~0.035 and ~0.06 for the HIGH and LOW structures, respectively. Although the μ value of ~0.05 for the WCN was lower than that of the LOW structure, it showed a weak response to wear resistance. As expected, the non-coated substrate showed the highest value [1].

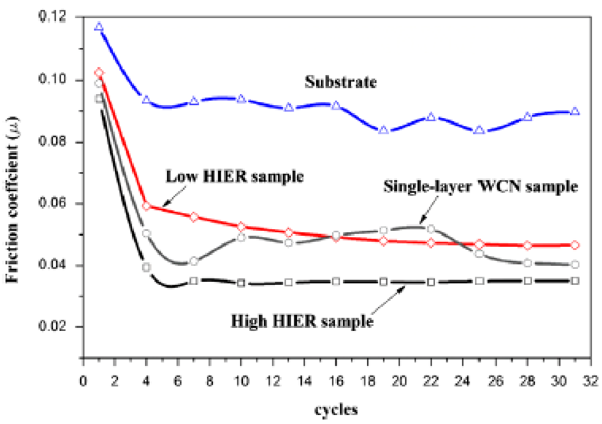


Figure 8. Friction coefficient properties shown in micro tribology test

Table 10. Friction coefficient of samples

Samples	Friction Coefficient
HIGH Hierarchy	~0.035
LOW Hierarchy	~0.06
WCN Monolayer	~0.05
Uncoated substrate	~0.095

The coefficient of friction value could be linked to the macrotribological experiment itself. When the samples were being tested, there was one tip that was able to penetrate the surface of the samples. It could be seen that the penetration of the tip into the HIGH structure was low. This was due to the hardness of the coating itself, which was arranged according to a hierarchical structure. Next, with the LOW structure, the low penetration of the tip showed that the contact area was small, thereby reducing the frictional force and thus, the coefficient of friction. For the WCN coating, the reading for the value of the coefficient of friction was low due to the presence of a carbon layer that acted as a strong barrier to friction [1].

Contribution of a Hierarchical Coating to the Mechanical Properties of the Coating

In terms of the mechanical properties, it can be seen in Table 11 that there were differences with regard to the strength, reduction in the elastic modulus, plastic index of H3/Er2 and creep. As predicted, the HIGH structure had the highest hardness followed by the LOW structure, WCN and substrate. To produce an increase in the hardness and elastic modulus, there was a decrease in the thickness of the HIGH architecture [1]. This was studied by [44], where they used coatings of Ti/TiN, Hf, HfN and W/WN and observed the increase in the hardness by reducing the thickness for each layer followed by the Hall-Petch relationship. The deviations in the material properties and the thickness of the interlayers controlled the mechanical responses in the nanoindentation test [1]. In previous studies, as shown in Table 12, it could be seen that the structure between the hard/soft layer and the hierarchy could produce a strength mechanism, while at the same time increase the wear resistance in the tribological system.

Table 11. Properties of samples

Samples	Hardness, H (GPa)	Reduced Elastic Modulus Er (GPa)	H3/Er2	Creep (nm/s)
HIGH Hierarchy	19.1 ± 2.1	223.0 ± 1.1	0.140	1.26
LOW Hierarchy	14.0 ± 1.5	115.7 ± 7.6	0.205	1.15
WCN Monolayer	11.96 ± 0.78	191.3 ± 6.3	0.047	0.82
Uncoated substrate	3.94 ± 0.12	46.00 ± 0.56	0.029	3.42

Table 12. Founding from other studies about multilayer hierarchy structure

References	Founding
[45]	Hard or soft interlayer can form protection where it will reduced the energy of crack propagation and increase hardness mechanism
[46]	Hierarchy system can increase the hardness mechanism in various length scale
[47]	Shear deformation can be reduce in multilayer coating if it contains layers that have different mechanical properties such as high and low elastic modulus

Contribution of Hierarchical Coating to the Tribological Properties of the Coating

The effectiveness of the hierarchical structure with regard to the tribological properties can be proven by the wear rate, as shown in Table 13. In the micro and macro tribological tests, the HIGH structure gave the lowest wear rate due to its hierarchical architecture. The HIGH structure also had a high wear resistance because of its high level of hardness as well as low crater wear in the wear track. The high hierarchical layer system in the HIGH structure was able to distribute the energy in the crack propagation and avoid the formation of larger craters. The hierarchical configuration can also design coatings in more specific applications by periodically varying the size of the multi-layers with different mechanical properties [1].

Table 13. Samples wear rate

Samples	Wear Rate ($mm^3N^{-1}m^{-1}$)
HIGH Hierarchy	2.2×10^{-4}
LOW Hierarchy	4.5×10^{-4}
WCN Monolayer	1.1×10^{-3}
Uncoated substrate	3.1×10^{-3}

CONCLUSION

In the manufacturing and machining industries, cutting is the key process in the production of quality products. Most of the cutting tools that are in use are made of cemented tungsten carbide. However, cemented tungsten carbide is inadequate when it comes to the issue of wear and a short lifetime. A coating is used as an alternative to extend the lifetime of the cutting tool and to improve the mechanical and tribological properties of the material. The use of multi-layered coatings for hierarchical structures is still very new and has yet to be studied in-depth. Different materials and thicknesses of the layers can be combined to achieve a maximum level of performance for the cutting tools. Depending on the material and the thickness of the layers, this hierarchical structure can improve the strength and hardness of the coating, reduce wear and prevent crack propagation. Most studies have focused on the material and thickness of the multiple layers but did not emphasize on the thickness of the individual layers. It is strongly recommended that more in-depth studies be carried out to investigate the effectiveness of a hierarchical structure with regard to the mechanical and tribological properties of cutting tool materials.

ACKNOWLEDGMENT

The authors would like to thank the Malaysia research foundation: Skim Geran Penyelidikan Fundamental: FRGS/1/2017/TK05/UKM/02/3 for funding this work within the project "Mechanical and Tribological Properties of Multilayer Coatings with a Hierarchical Architecture for the Metal Forming Industry".

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