INVESTIGATION OF MACHINING PERFORMANCE OF THE COATED CARBIDE CUTTING TOOLS WITH ACID ETCHING SURFACE PRETREATMENT

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ABSTRACT

This research investigated on machining performance of the coated carbide cutting tools with acid etching surface pretreatment. The main objective of this thesis is to investigate the effect of surface pretreatment using acid etching and physical vapour deposition coating (PVD) coating on tungsten carbide (WC) cutting tool. The effect of machining performance on tungsten carbide cutting tool using this pretreatment in term of wear rate also studied. The scope of work include tungsten carbide as cutting tool, acid hydrofluoric, HF for etching, PVD coating process and machining by turning operation. Tungsten carbide cutting tool was subjected to acid etching surface pretreatment for 20 minutes before it was deposited with PVD coating process. Next, the cutting tool was test by turning machine in order to determine the wear resistant and other material characterization also was performed such as surface morphology, hardness Vickers test and surface roughness test. The surface pretreatment with HF acid provide rough surface to tungsten carbide microstructure. Besides, the machining test performance shows the coated tungsten carbide with acid etching surface pretreatment provided longer tool's life compared to original tungsten carbide and coated tungsten carbide without surface pretreatment cutting tools. In addition, the hardness test indicated that average Vickers hardness of original tungsten carbide specimen was 970.7 HV while coated tungsten carbide with acid etching pre-treatment specimen was 1232.33 HV. In surface roughness test, the surface roughness of tungsten carbide increase after subjected to acid etching surface pretreatment but decrease after undergoes PVD coating process. From the result, the acid etching surface pretreatment and PVD coating process affect the mechanical properties of tungsten carbide cutting tool such as microstructure, hardness, surface roughness and wear resistance.

ABSTRAK

Kajian ini disiasat ke atas prestasi pemesinan alat karbida bersalut memotong dengan asid prarawatan permukaan punaran. Objektif utama tesis ini adalah untuk mengkaji kesan prarawatan permukaan menggunakan punaran asid dan salutan pemendapan wap fizikal (PVD) salutan pada tungsten karbida (WC) memotong alat. Kesan prestasi pemesinan karbida tungsten memotong alat menggunakan prarawatan ini dalam jangka kadar haus juga dikaji. Skop kerja termasuk karbida tungsten seperti memotong alat, asid hidrofluorik, HF bagi punaran, proses salutan PVD dan pemesinan dengan memutarkannya operasi.Pemotong karbida tungsten alat tertakluk kepada asid prarawatan permukaan punaran selama 20 minit sebelum ia didepositkan dengan proses salutan PVD. Seterusnya, pada alat pemotong adalah ujian dengan memutarkan mesin untuk menentukan haus tahan dan pencirian bahan yang lain juga telah dijalankan seperti morfologi permukaan, kekerasan Vickers ujian dan ujian kekasaran permukaan. Prarawatan permukaan dengan asid HF menyediakan permukaan kasar kepada mikrostruktur karbida tungsten. Selain itu, prestasi ujian pemesinan menunjukkan karbida tungsten bersalut dengan asid prarawatan permukaan punaran yang disediakan kehidupan alat yang lebih panjang, berbanding dengan karbida tungsten asal dan karbida tungsten bersalut tanpa permukaan prarawatan alat pemotong. Di samping itu, ujian kekerasan menunjukkan bahawa purata kekerasan Vickers spesimen karbida tungsten asal adalah 970.7 HV manakala karbida tungsten bersalut dengan asid punaran spesimen pra-rawatan adalah 1232.33 HV. Dalam ujian kekasaran permukaan, kekasaran permukaan peningkatan karbida tungsten selepas tertakluk untuk punaran permukaan prarawatan asid tetapi penurunan selepas menjalani proses salutan PVD. Daripada keputusan kajian ini, permukaan asid punaran pra-rawatan dan proses salutan PVD menjejaskan sifat-sifat mekanik karbida tungsten memotong alat seperti mikrostruktur, kekerasan, kekasaran permukaan dan rintangan haus.

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LIST OF SYMBOLS

µm	Micrometer
%	Percentage
g/cm^3	Gram per centimeter cube
kg/m^3	Kilogram per meter cube
Gpa	Giga Pascal
Mpa	Mega Pascal
c	Thermal Expansion Coefficient
K	Kelvin
HV	Hardness Vickers

LIST OF ABBREVIATIONS

CVD	Chemical Vapour Deposition
PVD	Physical Vapour Deposition
Ti-6Al-4V ELI	Titanium alloy alpha-beta Extra Low Interstitial
HF	Hydrofluoric
SEM	Scanning Electron Microscope
WC	Tungsten Carbide

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Tungsten carbide (WC) is one of the most famous tools and dies materials because of its high hardness, strength and wears resistance over a wide range of temperatures (Lee and Li, 2001). The amount of cobalt present was significantly affects the properties of tungsten-carbide tools. As cobalt content increases, the strength, hardness, and wear resistance of WC decrease, while its toughness increases because of high toughness of cobalt (Kalpakjian and Schmid, 1997).

There are many methods used to reduce the cobalt content and roughening the surface and one of them was chemical pretreatment. Intensive research has been carried out by previous researchers to reduce the cobalt content while roughening the substrate surface on tungsten carbide. Sarangi *et al*. (2008a) conducted a research by comparing between two types of pretreatment namely Murakami's reagent and HCl + HNO_3+ H_2O. It was observed the Murakami's reagent roughened the surface substrate while cobalt removal performed by HCl+ HNO_3+ H_2O. Sarangi *et al*. (2008b) also study the effect of HCl + HNO_3 + H_2O, Murakami's reagent and Murakami's reagent with Caro's reagent (H_2SO_4 + H_2O_2). It was reported that HCl + HNO_3 + H_2O was the higher reduction of Co content while Murakami's reagent with Caro's reagent was the higher of surface roughness.

The result of Murakami with Caro's acid was in a good agreement with Polini *et al*. (2000) and Kamiya *et al*. (2001). For reduction of cobalt content, both of them were obtained the same result that the nitric acid was better than Murakami's reagent. Nitric acid is better in terms of removing the cobalt content that will be roughening the surface of the cutting tool for the ease of coating layer. Sahoo and Chattopadhyay (2002) studied the effect of HNO_3 + H_2O, HNO_3 + HCl + H_2O, and HNO_3 + 3HCl on cobalt content and surface roughness. It was reported that HNO_3 + HCl + H_2O was the best pretreatment in term of reduction of cobalt content, roughening the surface, and improved diamond coating performance. In addition, Bu (2009) was found that Caro's reagent better than nitric acid in term of cobalt removal and surface roughness. While, Tang *et al.* (2002) and Ilias *et al*. (2000) were investigated on high temperature of nitric acid to evaluated better diamond coating.

In our research, the investigation on WC cutting tools will be done in term of surface morphology, hardness, surface roughness and wear resistance by carrying out several tests and machining. The effect of acid etching surface pretreatment and PVD coating on WC cutting tools will be evaluated to get the best performance of cutting tool.

1.2 PROBLEM STATEMENT

There are many factors that affect the performance of cutting tool especially when dry machining. The factors are such as the hardness, surface roughness and wear resistance and of the cutting tool. On other side, the cutting also facing problems such as low hardness and low wear resistance. Nowadays, there are many type of cutting tools invented by manufacture engineers to overcome this problem. As an example the coated and uncoated carbide cutting tools. This two cutting tools have their own advantages and disadvantages. Investigation had been made to determine what type of cutting tool was, whether coated or uncoated carbide cutting tool for dry machining aluminum alloy. Surface roughness is often a good predictor of the performance of a mechanical component, since irregularities in the surface may form nucleation sites for cracks or corrosion. Although roughness is usually undesirable, it is difficult and expensive to control in manufacturing. Decreasing the roughness of a surface will usually increase exponentially its manufacturing costs. This often results in a trade-off between the manufacturing cost of a component and its performance in application. For our study, we will conduct several experiments and testing to get the best cutting tool in machining performance.

1.3 OBJECTIVES

Basically, the specific objectives of this project are:

(i) To investigate the effectiveness of acid etching surface pretreatment and Physical Vapour Deposition (PVD) coating on tungsten carbide cutting tools.
(ii) To quantify the effect of tungsten carbide cutting tools wear resistance on titanium alloy alpha-beta Extra Low Interstitial (Ti-6Al-4V ELI) rod bar.
(iii) To determine the effect of machining performance of tungsten carbide cutting tools by analyzing the size and shape of titanium work piece chips.

1.4 SCOPE OF PROJECT

The identified scope of this project is as follows:

(i) The hydrofluoric acid (HF) was used for acid etching surface pretreatment.
(ii) Physical Vapour Deposition (PVD) coating technique used to coat the cutting tools.
(iii) Turning operation using 3mm diameter titanium alloy alpha-beta Extra Low Interstitial (Ti-6Al-4V ELI) rod bar work piece was used for dry machining.
(iv) The cutting tool was characterized in terms of surface morphology, wear resistance, hardness, surface roughness and work piece chips (due to type of cutting tool)

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Tungsten carbides were widely used in the cutting, drilling, milling, turning and molding tools. Surface pretreatment of the cutting tools can make the surface can be increased or reduced, it can be made ‘fresh’ (physisorbed or chemisorbed layers removed) or ‘passivated’, defects or other nuclei of crystallization can be introduced (Gordana, 2002). Meanwhile, diamond coating on these tools can improve their performance as well as their serving lives (Uhlmann *et al.*, 2001 and Stankovic *et al.*, 1998). In order to find the best cutting tool, the substrate properties in terms of surface morphology, hardness, surface roughness and wear resistance have been studied.

2.2 CUTTING TOOL MATERIALS

The cutting tools must meet several requirements, depending upon the cutting conditions and the work piece material. In particular, the cutting tools need to have high hardness and high wear resistance. It also has to be tough, chemically stable over a wide range of temperatures (up to $1000^{o}C$) and inert to the work piece material. It is difficult to satisfy all the demands in one material, and thus best tools are often made of hard coatings on suitable substrate.

Cutting tool materials are required to have several properties that enhance the efficiency of the material removal process (Anon, 2009). The main requirements for cutting tool materials are as follows:

(i) High wear resistance
(ii) High-temperature physical and chemical stability
(iii) Toughness or high resistance to brittle fracture

2.2.1 Aluminum Oxide (Al_2O_3)

Al_2O_3 is a widely used advanced ceramic including as a cutting tool in turning operation (Ramli *et al.* 2012).From the pure Al_2O_3, the ceramic cutting tool is made. The hardness and chemical inertness make ceramics a good material for high-speed finishing and/or high-removal-rate machining applications of super alloys, hard-chill cast iron, and high strength steels. Since ceramics have poor thermal and mechanical shock resistance, interrupted cuts and interrupted application of coolants can lead to premature tool failure. Besides, ceramics are not suitable for aluminium, titanium, and other materials that react chemically with alumina-based ceramics.

2.2.2 Tungsten Carbide

Tungsten Carbide is an inorganic chemical compound (specifically, a carbide) containing equal parts of tungsten and carbon atoms. Tungsten carbide is widely used in industry because of its extraordinary properties (Huai, 2009). Its extreme hardness which is about 8.5–9.0 Mohs scale and good wear resistance makes it very useful in manufacture of cutting tools. They are suitable to cut a variety of materials such as gray cast iron, ductile nodular iron, austenitic stainless steel, nickel-base alloys, titanium alloys, aluminum, free machining steels, plain carbon steels, alloy steels, and martensitic as well as ferrite stainless steels. Wear resistance of tungsten carbide is better than that of wear resistance tool steels. In conditions that are including abrasion, erosion and galling, it wears can up to 100 times longer than steel. Tungsten carbide is approximately three times stiffer than steel, with a

Young's modulus of approximately 550 Gpa. The primary properties of tungsten carbide are its high strength and low ductility at high temperatures. Others properties of tungsten carbide are:

(i) High thermal conductivity
(ii) Low electrical resistivity (1.7 – 2.2×10^7Ohm.m)
(iii) High resistance to corrosion
(iv) High fracture strength
(v) Heat and oxidation resistance
(vi) High melting point (3410°C)
(vii) High rigidity
(viii) High strength
(ix) High impact resistance

Table 2.1: Comparison of properties of tungsten carbide and other cutting tool materials

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

Source: Anon (2009)

2.3 SURFACE PRETREATMENT

Surface pretreatment is the use of mechanical, chemical or physical methods to remove strongly absorbed surface layers and activate the surface. The reason of surface pretreatment is carrying out:

(i) To remove completely/prevent formation weak boundary layers
(ii) To increase the adhesion strength of the substrate-coating interface.
(iii) Optimize the degree of intimate molecular contact between adhesive and adherent to form an effective bond.

Among the general methods that are used in surface pretreatment are mechanical method, chemical method and physical method. The examples of surface pretreatment are like sand blasting, Murakami solution etching and acid etching.

2.3.1 Sandblasting

Kulkarni *et al.* (2011) have mentioned that tensile bond strength (TBS) of sandblasted surface specimens decreased when compared with the smooth surface while the shear bond strength increased, implying that the bond strength will depend on the test method used. Theoretically, sandblasting increases surface area and provides mechanical locks at bond site and should result in stronger bonds. The use of the commercially available silica-coated alumina particles for sandblast was significantly effective for increasing bond strength than the conventional alumina (Wang *et al*., 2010). Sandblasting with alumina (Al_2O_3) is one of the methods that are recommended for creating surface irregularities and providing mechanical interlocking force for porcelain.

2.3.1 Acid Etching

Acid etching involves immersing a metal substrate in an aqueous acid solution to remove a loose layer of oxide from its surface. This surface pretreatment provides enough surface preparation for bonding. Lu *et al*. (2006) reported succeeding acid etching would only decrease the surface roughness slightly, subsequently that the surface was still rather rough after the acid etching process.

Table 2.2: Advantages and disadvantages of acid etching

Advantages	Disadvantages
• Provide smooth and bright surfaces • The etched surface topography has a finer more uniform • Low sensitivity to microstructure features	• The vapor containing hydrofluoric acid has to be completely eliminated

Source: Lu *et al*. (2006)

2.4 COATING

Coated tools should be considered for most applications because of their longer life and faster machining. The coating layers help to increase the performance of cutting tools, consequently increase the machining productivity (Ezugwu *et al.*, 2003; Che Haron *et al.*, 2007). The reason of coating is to improve surface properties of the substrate, such as appearance, adhesion, corrosion resistance, wear resistance, and scratch resistance. The common coating techniques available in industry nowadays are:

(i) Chemical Vapor Deposition (CVD)
(ii) Physical Vapor Deposition (PVD)

2.4.1 Chemical Vapor Deposition (CVD) Coating

CVD is a generic name for a group of processes that involve depositing a solid material from a gaseous phase. This coating technique is quite similar in some respects to PVD. PVD differs in that the precursors are solid, with the material to be deposited being vaporized from a solid target and deposited onto the substrate. These are the examples of CVD processes:

(i) Atmospheric Pressure Chemical Vapour Deposition (APCVD)
(ii) Low Pressure Chemical Vapour Deposition (LPCVD)
(iii) Metal-Organic Chemical Vapour Deposition (MOCVD)
(iv) Plasma Assisted Chemical Vapour Deposition (PACVD) or Plasma Enhanced Chemical Vapour Deposition (PECVD)
(v) Laser Chemical Vapour Deposition (LCVD)
(vi) Photochemical Vapour Deposition (PCVD)
(vii) Chemical Vapour Infiltration (CVI)
(viii) Chemical Beam Epitaxy (CBE)

2.4.2 Physical Vapor Deposition (PVD) Coating

PVD coating is a thin-film deposition process in which a material (metal, alloy, compound, cermet, or composite) is either evaporated or sputtered onto a substrate in a vacuum. Some of the main reasons of PVD coatings are used:

(i) improved hardness and wear resistance
(ii) reduced friction
(iii) improved oxidation resistance
(iv) increase tool life
(v) improve corrosion resistance contributes to better surface quality

The use of such coatings is aimed at improving efficiency through improved performance and longer component life. They may also allow coated components to be operated in environments that they have been able to perform compared to the uncoated components. The uncoated components are not allowing for high cutting speeds and thus increasing both the time required for machining operation and production costs. PVD coatings are generally used to improve hardness, wear resistance and oxidation resistance. Thus, such coatings use in a wide range of applications such as:

(i) Aerospace
(ii) Surgical/medical
(iii) Dies and moulds for all manner of material processing
(iv) Cutting tools

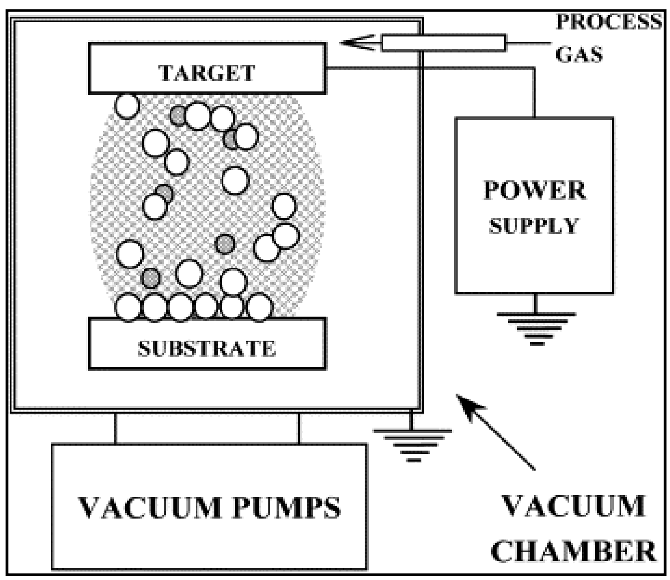

Figure 2.1: Schematic diagram of PVD sputtering chambers and process.

Source: Malshe *et al.* (2001).

2.4.3 COATING MATERIAL

2.4.3.1 Diamond like carbon

Diamond like carbon has its own advantages as an ideal surface coating material like; good corrosion resistance, high wear resistance, low friction characteristics, high hardness, and good chemical resistance. While the properties of diamond like carbon are as Table 2.2:

Table 2.3: Diamond-like carbon properties

Properties	Value
Density	1.5 – 2.2 x 10^3 kg/m^3
Co-efficient of friction	0.1 - 0.2
Hardness	900 – 4000 HV
Coating thickness	10 nm – 4.0 μm
Thermal conductivity	2 m·K

Source: Robertson (2002)

2.5 WORK PIECE

2.5.1 Titanium alloy alpha-beta Ti-6Al-4V Extra Low Interstitial (Ti-6Al-4V ELI)

Daymi (2009) have said that, “Titanium alloys are known for their application in biomedical devices, such as hip prosthesis and bone plates, since many decades, in the aerospace, automotive and petroleum industries because of their good strength-to-weight ratio and superior corrosion resistance.” Among all titanium alloys, Ti–6Al–4V is the most widely used. The chemical composition and physical properties of work piece material are given in Tables 2.4 and 2.5, respectively. At least 3 mm of material at the top surface of work piece was removed in order to eliminate any surface defects and residual stress that can adversely affect the machining result (Kalpakjian and Schmid, 2001).

Table 2.4: Chemical composition of Ti-6Al-4V ELI (wt %)

HEAT	C	Si	Fe	Ti	Al	N	V	S	O	H	Y
C-11465	0.11	< 0.03	0.18	Bal.	6.1	0.007	4.0	< 0.003	0.11	0.0031	< 0.005

Source: Che Haron *et al.* (2009)

Table 2.5: Physical properties of Ti-6Al-4V ELI

Tensile (kPa)	2% Yield (kPa)	4D. Elong. 5D (%)	% R.A
910.108	820.476	17.0/14.0	42.0

Source: Che Haron *et al.* (2009)

2.6 DRY MACHINING

Dry machining is ecologically desirable and it will be considered as a necessity for manufacturing enterprises in the near future. Industries will be compelled to consider dry machining to enforce environmental protection laws for occupational safety and health regulations. The advantages of dry machining include: non-pollution of the atmosphere (or water); no residue on the swarf which will be reacted in reduced disposal and cleaning costs; no danger to health; and it is non-injurious to skin and is allergy free. Moreover, it offers cost reduction in machining. (Narutaki *et al.*, 1997). The dry machining was selected in order to avoid the uses of degradable coolants, which are harmful for human and degrade the environment (Che Haron *et al.*, 2007).

2.6.1 Turning Operation

Turning is a form of machining, a material removal process, which is used to create rotational parts by cutting away unwanted material. The turning process requires a turning machine or lathe, work piece, fixture, and cutting tool. The work piece is a piece of preshaped material that is secured to the fixture, which itself is attached to the turning machine, and allowed to rotate at high speeds. The cutter is typically a single point cutting tool that is also secured in the machine, although some operations make use of multi-point tools. The cutting tool feeds into the rotating work piece and cuts away material in the form of small chips to create the desired shape.

Turning is used to produce rotational, typically axis symmetric, parts that have many features, such as holes, grooves, threads, tapers, various diameter steps, and even contoured surfaces. Parts that are fabricated completely through turning often include components that are used in limited quantities, perhaps for prototypes, such as custom designed shafts and fasteners. Turning is also commonly used as a secondary process to add or refine features on parts that were manufactured using a different process. Due to the high tolerances and surface finishes that turning can offer, it is ideal for adding precision rotational features to a part whose basic shape has already been formed. The manual handling turning operation machine that is common used in mechanical laboratory is Conventional Lathe Machine model of ERL – 1330 as shown in Figure 2.2.

Figure 2.2: Conventional Lathe Machine, Model: ERL – 1330

Source: General Machining Laboratory, Faculty of Mechanical Engineering, Universiti Malaysia Pahang. (2012)

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

This chapter discussed methodology of the project in general, with a specific focus to investigate the effect of acid etching surface pretreatment on tungsten carbide. The work include as a scope of research. Tungsten carbide cutting tool was subjected to acid etching surface pretreatment for 20 minutes. Then, it was deposited with coating process. The physical vapor deposition coating technique was used with hard carbon material coating. Next, the cutting tool was test by turning machine in order to determine the wear resistant. Other material characterization also was performed such as surface morphology analysis through SEM images, Vickers hardness test, surface roughness test and work piece chips analysis. The detail progress of this research is shown in Figure 3.1.