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Effect Ti/AlTiN Multilayer Coating on the Crater Wear Process of Cutting Tool and Tribological Properties

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Abstract

Tool wear is a major problem in machining operations because the resulting material loss gradually changes of the machine tool. There many factors may leads to material loss like; friction, corrosion, and also it's happened by rubbing during machining processes between the work piece and the tool. Dimensional accuracy of the work piece, and also the surface finish will be reducing by tool wear. It can also increase cutting force. In this study, we focused on the effect of the coating process on crater wear problems. Crater wear is caused by the flow between the chip and the rake face of the tool, whereas flank wear is caused by the contact between the tool and the work piece. In reducing crater wear, aluminum titanium nitride (AlTiN) using $Al_{0.67}$ $Ti_{0.33}$ in cathodic arc plating system is considered effective as a tools coating material. In reducing flank wear, AlTiN is also deemed as the best tool coating material. Experimentally, the use of Ti/AlTiN-coated tools has been proven effective in reducing crater wear. In this study, the roughness Ra values of the (Ti/AlTiN) coatings were (0.14, 0.15, 0.23, 0.02, 0.21) μm at values of layers thickness (1.138, 1.518, 1.735, 2.717, 3.0818) μm, respectively. The lowest COF appeared at thickness 2.717 μm and the high coefficient of friction of the Ti/AlTiN coating was a result of high roughness and the large contact surface area of the system coating steel ball. The two most important parameters used to measure crater wear are length and width of wear.

Keywords: *Tool life, work piece, crater wear,* AlTiN, *COF.*

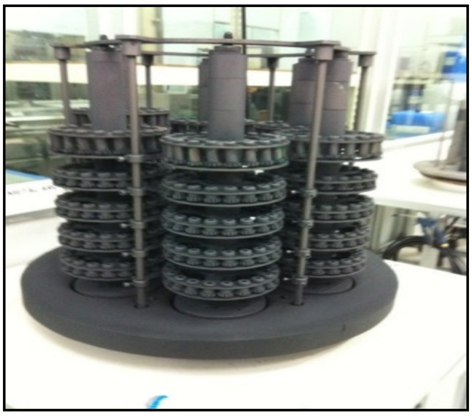
1. Introduction

Tool wear is a major problem in machining operations. According to [1], tool wear is a gradual change in the shape of the machine tool as a result of material loss. Material loss occurs because of friction, abrasion, and the rubbing process that take place between work piece and the tool. during machining. Tool wear results from progressive loss and the degradation of the machining tool material. Tool wear may decrease many important properties in the work piece like surface finish, dimensional tolerance, and accuracy. Moreover, tool wear may increase machining forces and decrease the production efficiency of the work piece [1, 2]. Tool wear may also increase the vibrations of the production machine during operation as well as the temperature at the contact points between the tool and the work piece. Researchers have identified tool wear as the dominant problem in the life of machine tools. Therefore, reducing the wear of machine tools enhances their life span. Although cutting fluids are commonly believed to be capable of reducing tool wear, a research has shown that these fluids do not necessarily reduce the wear of machine tools [2]. The applications of TiN coatings and their properties have been wildly explored by many researchers. Other thin coatings are usually added to prolong the life span of the elements comprising industrial parts, such as Al, Ti and Cr, as well as to increase oxidation resistance at temperatures above 450°C. In engineering applications TiAlN coatings was developed to be an alternative to TiN coatings [6-8]. The next logical step in improving properties (high coefficient of friction [COF] and refractoriness) is to develop TiAl -based coatings as thermal barriers [9]. In fact, further research has indicated that cutting fluids can promote tool wear [3]. Two common methods have been proven effective in reducing tool wear [9-10].These methods are the operation of the machine under conditions that cause lower tool wear and the tool and the incorporation of wear-resistant materials into the machine tool. Ti/AlTiN coatings using $Al_{0.67}Ti_{0.33}$ cathodes in a cathodic ion plating system are report on in this paper. The effects of thickness layer on the mechanical properties of the coatings, and modulation period are determined.

2. Experimental Details

The multilayer coating of cutting tools using Ti/AlTiN is important in improving cutting tools and their life span (Figure1: a & b). ARC system technology was developed by J&L Technology Korea (Model legend: H.I.P III) are conducted in this experimental study. This system are involves from four rounds AlTi 0.67: 33% target and four Ti targets diameter of (15 ×150) mm. The holder of substrate jig contains from triple rotations with six axes, as shown in Figure 1. The thermocouple is located at the back of the substrate jig holder with high, mid, and low levels from top to bottom. The distance between the thermocouple and the substrate holder is approximately 20mm – 30mm.

(a)



(b)

Fig. 1. (a) PVD in cathodic arc plating system technology sophisticated by J&L Korea (Model legend: H.I.P III). (b) Substrate holder outside coating chamber.

This is feedback loop in the chamber regulates the power of the induction heater for temperature control. With the presence of nitrogen gas in the coating chamber; AlTiN coating will deposited on the substrate, and by the bombardment of argon ion; the ARC of the target material (Ti and AlTi) will induced. The substrate is a WC square cutting insert that measures (3.18× 12.7 × 12.7) mm. Figure 2). Prior to coating, the cutting insert underwent ultrasonic cleaning with a detergent bath using different detergents and cleaning durations, as shown in Table1.

The rotating turntable is holding the cutting insert with5 rpm rotation speed, and the approximate distance from the target to the substrate is 50 mm. the experiment of coating process consists from six stages: they are pumping, main layer coating (AlTi), cooling, heating, ion etching, and buffer layering (Ti). The minimum value of pressure which required in this process is (5×10^{-5}) mbar. A process setting for the six stages was included. Table (1) listed in detail all the multilayer coatings parameters.

Table 1,
Parameters for the arc ion plating of AlTiN multilayer coatings.

Step	Process	Parameters
1	Pumping	Rotary pump, root pump and turbo molecular pump
2	Heating	Induction heater for heating the substrate up to the set process temperature
3	Ar bombardment and ion cleaning	Ultimate vacuum=5.0×10^{-5} mbar, bias voltage = 900Vwith 80% duty cycle, argon gas flow = 100 sccm, arc source current = 100A,time= 30 mins, temperature =380 C°
4	Buffer layer	Bias voltage = 30V, nitrogen gas flow = 300 sccm, arc source current=100A, time = 10 mins, temperature = 380 C°
5	Main layer AlTiN multilayer coating deposition	Bias voltage = 40v, nitrogen gas flow = 600 sccm, arc Source current 80A, time = 45 mins, temperature = 380 C°
6	Cooling down and venting	Natural cooling for 30min at 100 ◦C

3. AlTiN Coating Deposition

The parameters setting for main AlTiN coating layer deposition processes are shown in Table 2. The Figure 2 shows all details in of the flow for coating deposition process and more specification and function both operation elements.

Table 2,
Main layer parameters

40 V	Bias voltage
600 SCCM	Nitrogen gas flow
80A	Arc source current
45,80,100,120,and 135 minutes	Time
380C°	Temperature

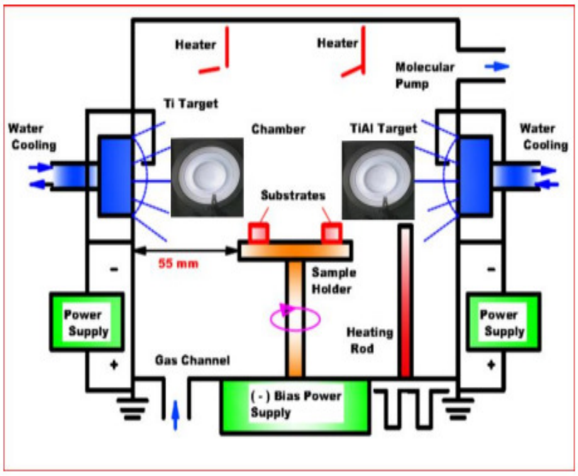


Fig. 2. Schematic diagram of the arc ion plating system.

The complete deposition procedure has been described earlier. A summary of the deposition parameters can be seen in Table 3.

After the completion of the coating process, the coated tools were cooled in the chamber naturally for 60 minutes.

Table 3,
Deposition parameters

Rotation Speed rpm	AlTiN deposition time (min)	Total layer thickness (μm)	Ar gas flow rate (sccm)	Bias voltage (−V)	Buffer layer (min)	N_2 gas flow rate (sccm)	Etching (min)	Substrate temperature (C°)
5	45	2.717	100	40	10	600	30	380
5	80	3.089	100	40	10	600	30	380
5	100	3.912	100	40	10	600	30	380
5	120	5.815	100	40	10	600	30	380
5	135	8.760	100	40	10	600	30	380

4. Pretreatment of Substrate

The cutting insert must be cleaned before coating by ultrasonic with a detergent bath for different mixed detergent and time as shown in Table 4 using ultrasonic system shown in Figure 3.

Table 4,
Cleaning Procedure

Tank #	Solvent	Time (sec)	Temperature (°C)	Condition
1	HT1401(1) + HT1170 + DI water	300	52	Rotation
2	HT1401 + HT1170(2) + DI water	300	52	Rotation
3	DI water			Spray & Rotation
4	HT1233(3) + ANTICORR + DI water	150	52	Rotation
5	DI water			Ultrasonic & Rotation
6	DI(4) water (Rinsing)			Rotation

DI) water: The processed and pure water, or mechanically filtered to be cleaned and ready for consumption. The most common forms of purified water is distilled water and deionized (DI).

Fig. 3. The cutting insert was cleaned by ultrasonic with a detergent bath for different mixed detergent and time.

5. Study on Crater Wear

To understand this type of tool wear, reviewing the geometry of machine tools is important. Figure 4 illustrates the general geometry of a turning tool. Table 5 present the geometry of the turning tool. The tool angle affects tool wear and the life span of the tool [3]. Crater wear results from the erosion of the rake face caused by cutting chips. The figure below illustrates the chip flow in orthogonal cutting.

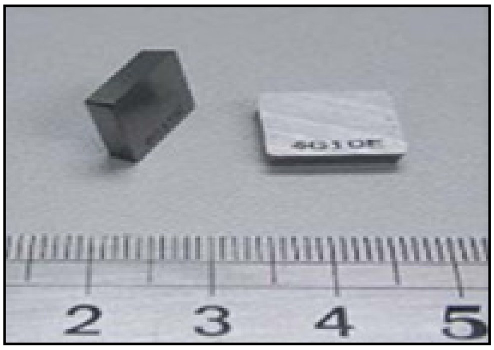
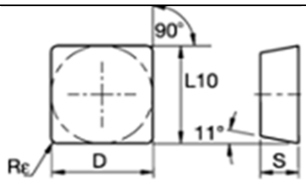


Fig. 4. Tungsten carbide cutting tool insert commercially made by Sumitomo.

Table 5,
Sumitomo SPGN120208S cutting tool dimensions

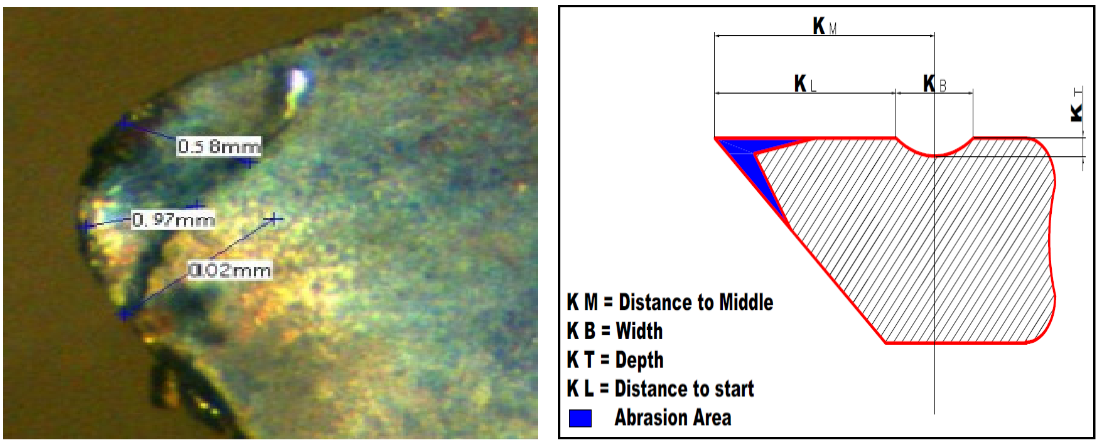


Sumitomo SPGN120308S
Dimension:

- D = 12.7mm
- S = 3.18 mm
- R_E = 0.8 mm

Figure 5a clearly shows that the chip flows over the rake face of the cutting tool during machining .The contact between the rakes face and the chip causes high friction at the interface. Consequently, continuous flow can increase friction that leaves a scratch or scar on the face of the tool, which is usually parallel to the cutting edge of the tool [4]. This scar is generally in the form of a crater, hence the term crater wear. Crater wear increases the rake angle, which in turn reduces the cutting force. However, crater wear weakens the tool cutting edge and thus reduces its strength [5]. The (figure5a) illustrates crater wear on the rake face of a cutting tool.

Figure 5(b) shows the variables that usually characterize crater wear. The most important parameter for wear characterization is crater depth (KT). Studies on crater wear show that the spindle speed of the cutting machine has an indirect relationship with crater wear [4]. Extremely low spindle speed causes chip buildup on the rake face. This buildup increases friction, which causes the formation of a crater on the rake surface. The figure below illustrates the effect of cutting speed on crater wear and tool durability. Figure 6 shows that increase in cutting speed reduces crater wear, thereby increasing the tool life.



(a) (b)

Fig. 5. Characteristics of crater wear.

The variation in crater wear with time is shown in Figure 6. Three stages of wear can be identified. The wear rate in first stage is small, but this wear will increase gradually to become in average value. In third stage, the rate of wear will be very fast and decrease the tool life. In stage 1, tool wears ranges from 0 μm to 1.8 μm only within 0 to 10 min of machining. In stages 2 and 3, we found that; when the machining time increases, the crater wear will increase. In this case the approximating time for tool fails during machining is about (35) minutes.

6. Results and Discussion

6.1: Types of tool wear and how to measure them

Friction between the tool and the work piece during cutting/machining generates high stresses and produces a wear pattern on the flank and the rake faces of machine tools [6]. Crater and flank wears are the most significant types of wear. As discussed previously, crater wear occurs on the rake surfaces of tools (Figures 5 to 8). Four parameters characterize or measure crater wear [5,7], as shown in Figure 8. These parameters include crater depth, width, and distance from the beginning to the middle. Depth is the most widely used parameter for evaluating and measuring crater wear. It is typically used to determine the effect of cutting speed on crater wear. The figure below illustrates the effect of speed on crater wear. Figures (7, 8) and characterizes the cutting time, depth, and width of the crater parameters.

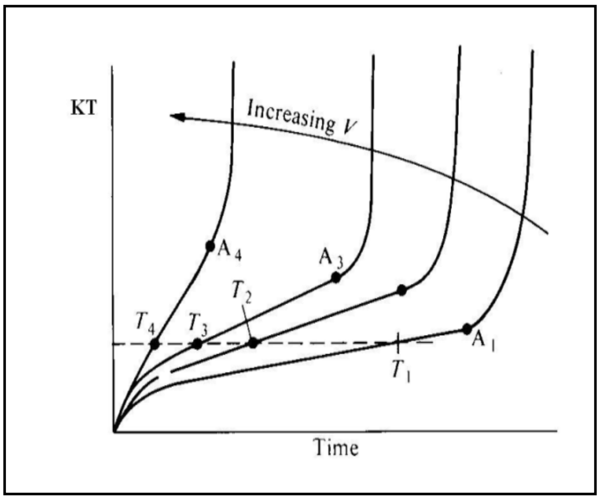


Fig. 6. Effects of cutting speed on crater Wear depth. [14].

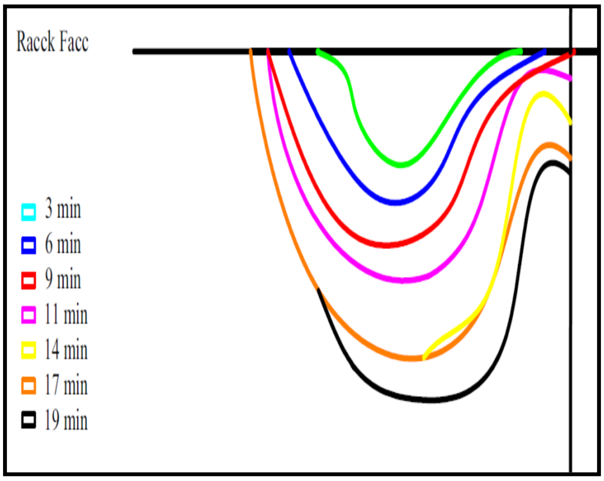
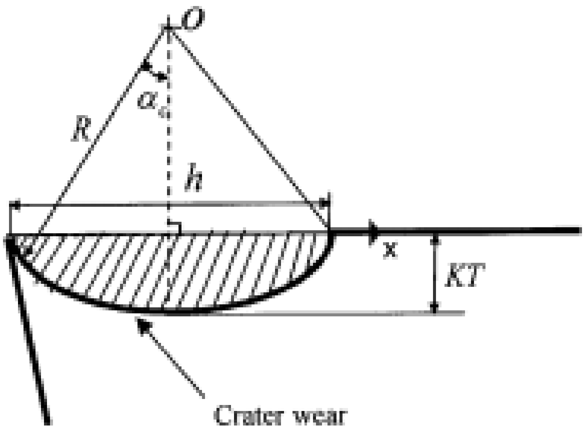


Fig. 7. Width and depth as measurements of crater wear.

Using tool geometry and crater parameters (as shown in the figure 8,a), [4] proposed the following equations (equation 1) for measuring crater wear in machine tools mathematical and the optical microscope(figure 8, b). In this paper the crater wear was calculated using the optical microscope method. Thickness measurements were conducted on a brittle fracture surface of a sample. SEM micrograph of the evaluated coatings together with Energy Dispersive X-ray analysis (EDX) which was performed in nitrogen atmosphere to determine the elements contents in substrate as such shown in Figure 9.

$$R^2 = (\frac{h}{2})^2 + (R - K_T)^2 \qquad \ldots(1)$$

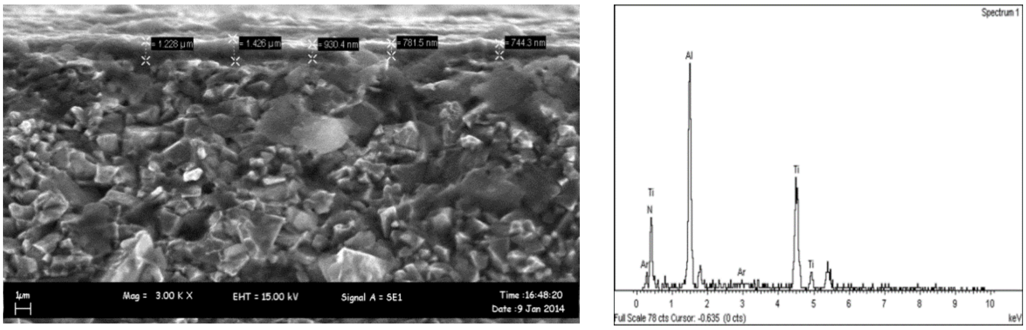


where
R = Radius
h =Contact length.

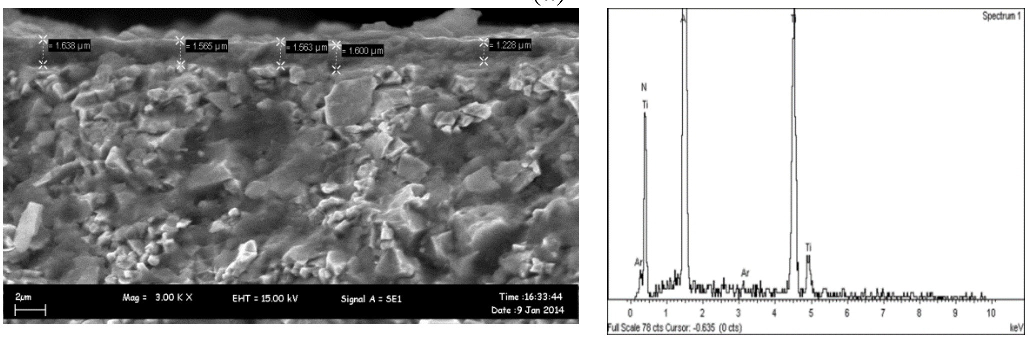
(a)

(b)

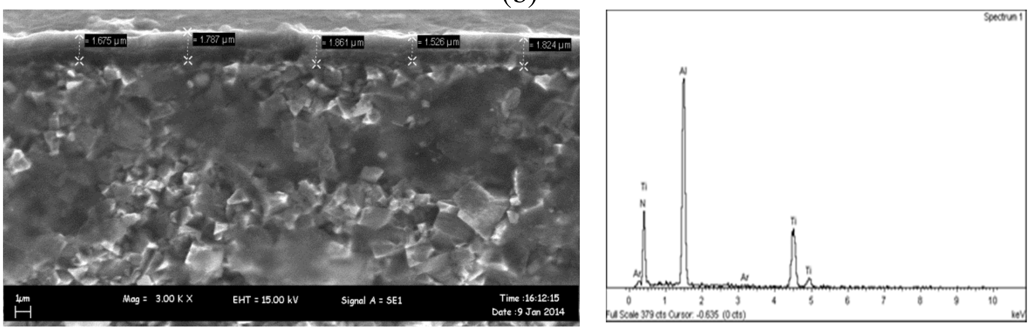
Fig. 8. (a): Estimating dimensions of crater wear arithmetically. (b): Optical microscopy used in of measured crater wear in this paper.



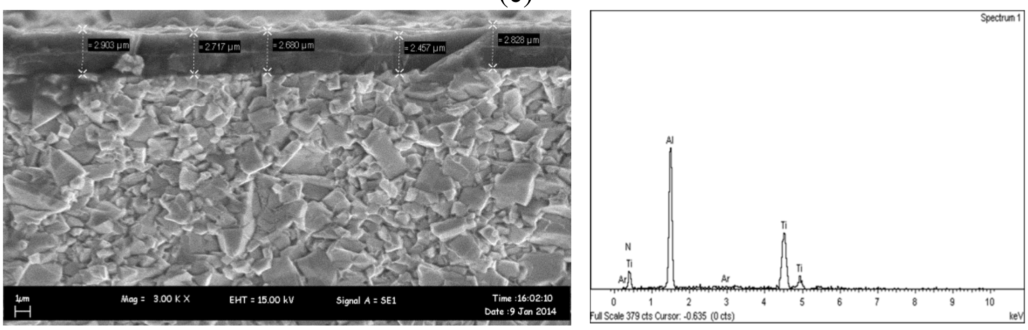
(a)



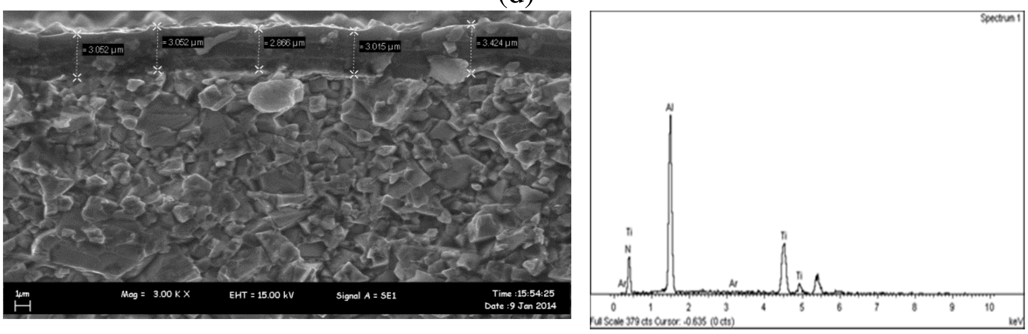
(b)



(c)



(d)



(e)

Fig. 9. a, b, c, d, and e Brittle fracture (micrograph) and SEM/EDX spectrum of Ti/AlTiN, thickness 1.183 to 3.081μm

6.2. Tribological properties

Figure 10: shows the COF of the sliding time for the TiN/AlTiN multilayer coatings and the tungsten carbide specimen at room temperature. After 0 s to 200 s, the COF of the substrate reached 0.63. Given the extreme hardness at the thickness layers of 3.0818 µm, the wear process was deemed stable. However, the TiN/AlTiN coatings at the thickness layers of 1.735 µm notably exhibited low hardness, which indicated that their wear resistance was better than that of other TiN/AlTiN coatings

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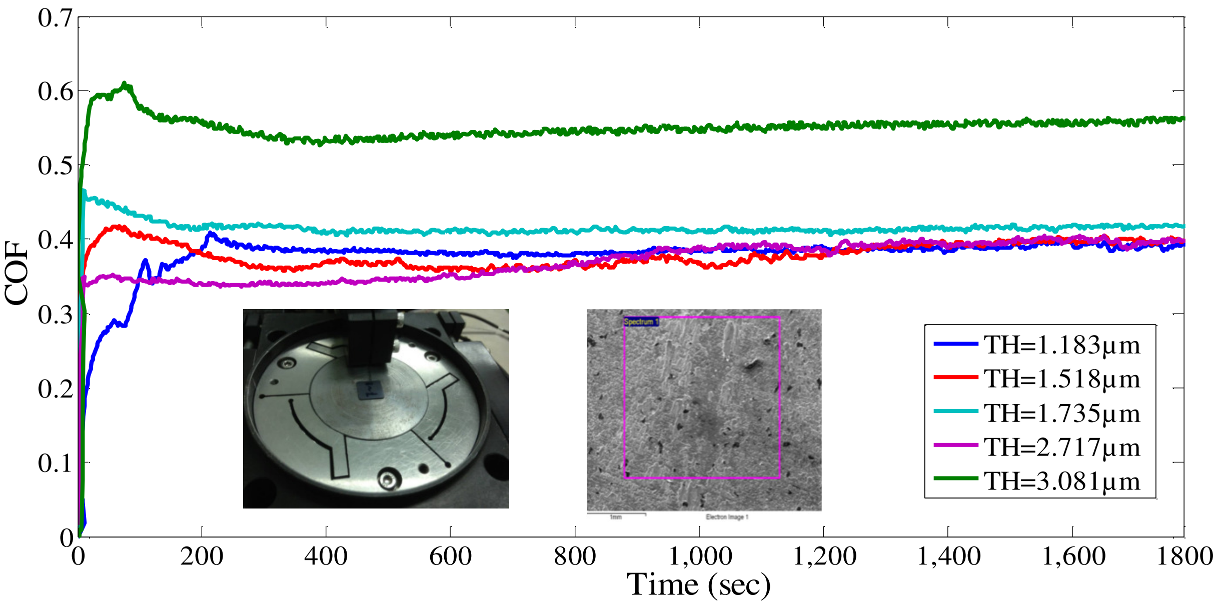


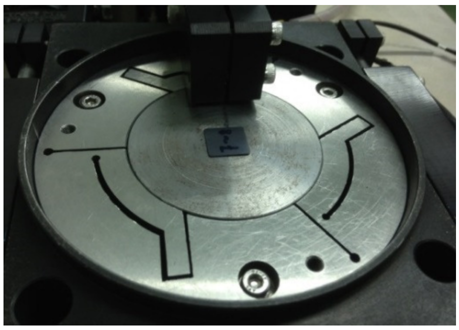
Fig. 10. COF of Ti/AlTiN multilayer coating of substrate with different thickness layers.

There are some of wear scar will appear at a thickness layer of (3.0818) µm on the multilayer coatings deposited surface of the Ti/AlTiN. Normally a transferred layer will cover the wear scar, which was composed mainly of Fe and several Fe oxides (as shown in Table 6).Using energy dispersive X-ray analysis (EDX) which was performed in nitrogen atmosphere to determine the elements contents in substrate as such shown in Table 6.

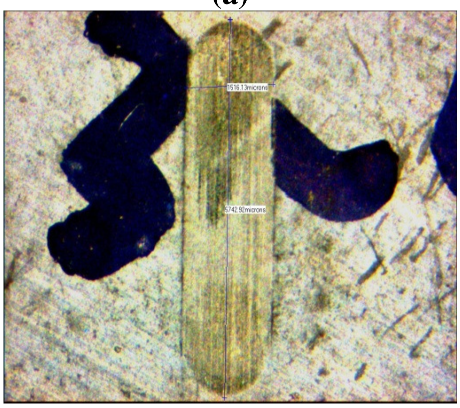
Table 6,
Elements of the wear debris of Ti/AlTiN multilayer coatings at thickness layer of 3.0818 µm.

Element	Wt.%	At. %
O	23.34	50.91
Ti	11.36	8.28
Fe	65.30	40.81

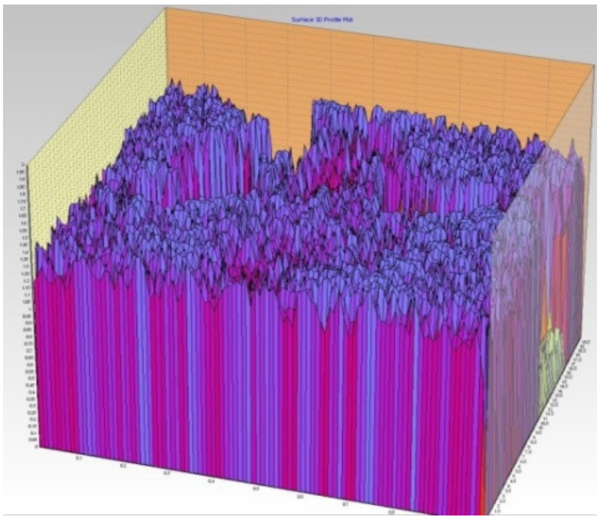
The hardness of Ti/AlTiN coatings is very high relative to the hardness of GCr15 debris ball which generated during the wear process. Due to tribo-oxidation happened in this process, the wear debris was accumulated, entrapped and broke into minute fragments [11–13]. Some large wear scar will appear on the surface due to debris adhered by coating



(a)



(b)



(c)

Fig. 11. shown 3D zoom 20x, the optical microscope have been used to observe the morphology of the wear track and wear debris. (a) prepare specimen before dispersion (b) the wear track, (c) 3D for wear.

Figure 12: presents the COF of the evaluated coatings based on sliding distance. The COF of the Ti/AlTiN coating grew markedly after traveling 7 and 15 m and then reached its maximum. In the case of the AlTiN coating, COF gradually rose to its maximum. The COF of the AlTiN coating grew linearly after traveling 18 m and then gradually reached its maximum. The COF was influenced mainly by roughness Ra, coating hardness, and contact surface area. The figures above show the width of the wear track a, which demonstrates good agreement with the volume loss of the evaluated coatings. Wear–coating volume loss was lowest for the AlTiN coating at a thickness of 1.138 um. Meanwhile, the COF values of the AlTiN coating were the highest ones. Increasing in contact area between the coating–counter-specimen systems is the main cause of COF growth. The wear of the counterpart was not investigated.

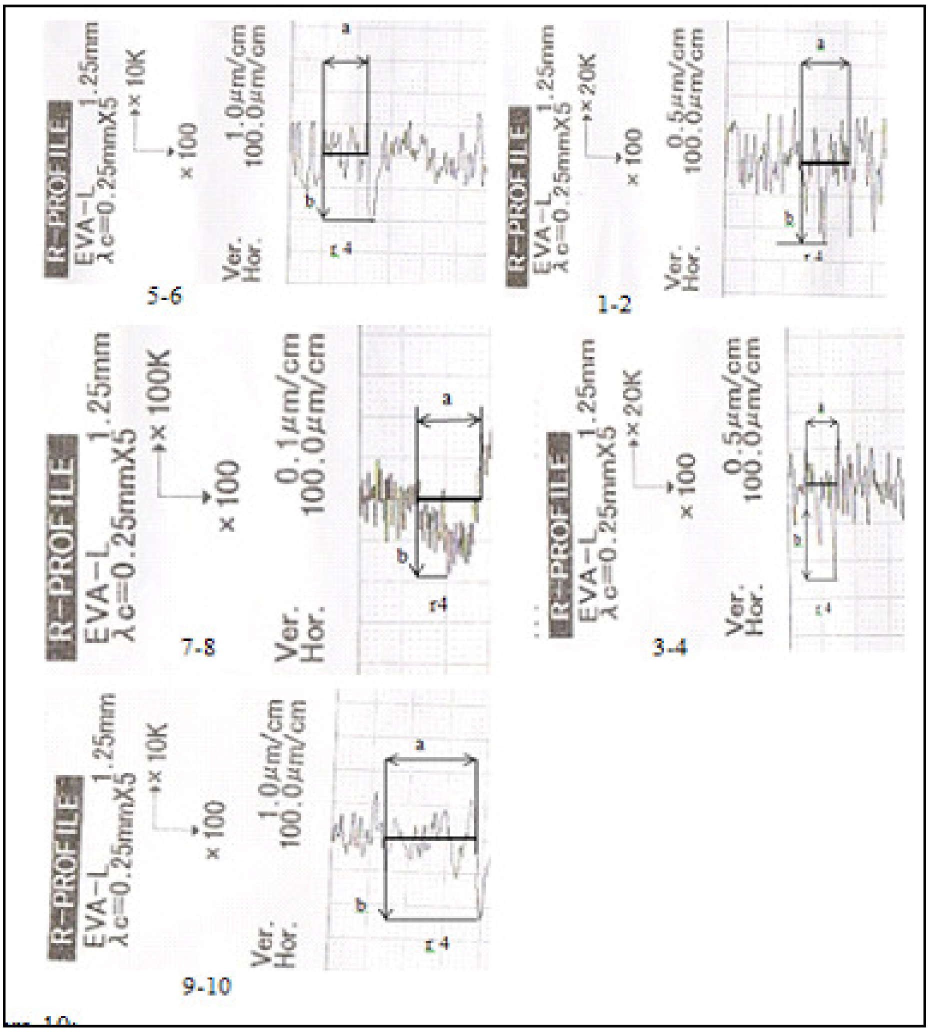


Fig. 12. Profile of the cross sections of the wear tracks of Ti/AlTiN coating after pin-on-disc testing: a, width; b, depth; and r4, radius of sliding track.

7. Conclusion

Tool wear is the main problem in machining operations. It is characterized by a gradual change in the shape of the machine tool resulting from material loss. Material loss is caused by the friction, abrasion, and the rubbing process that take place between the tool and the work piece during machining. Tool wear results from progressive loss and the degradation of the material of the machining tool. It decreases the dimensional accuracy and surface finish of the work piece and increases cutting forces. Crater wear occurs because of the contact between the chip flow and the rake face of the tool. Flank wear occurs because of the contact between the tool and the work piece. Ti/AlTiN is the best tool coating material for reducing crater wear and flank wear. The depth and width of the wear are the most significant parameters in measuring crater wear. Researchers have developed several models for the measurement of crater and flank wear in machine tools. The effect of thickness layer on crater wear and the tribological wear properties of Ti/AlTiN multilayer coatings were investigated in this work. The roughness Ra values of the Ti/AlTiN coatings were 0.14, 0.15, 0.23, 0.02, and 0.21 μm at thickness layers of 1.138, 1.518, 1.735, 2.717, and 3.0818 μm, respectively. The high COF of the AlTiN coating was a result of high roughness and the large contact surface area of the system coating ball. Minimum values of surface roughness will reach 0.02 μm at a thickness layer of 2.717 μm.

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تأثير طلاء(Ti/AlTiN) متعدد الطبقات على عملية تأكل عدة القطع وخصائص الاحتكاك على سطحها

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الخلاصة

يعد تآكل عدة القطع مشكلة رئيسة في عمليات التشغيل الميكانيكي لأن الخسارة المادية الناتجة هو تغير تدريجي في أداة القطع و سبب هذه الخسارة المادية هو التآكل والاحتكاك، وعملية الفرك التي تحدث بين الأداة وقطعة العمل أثناء عمليات التشغيل . تأكل عدة القطع يمكن أن تقلل من دقة الأبعاد وجودة تشطيب السطوح لقطعة العمل , وايضا يؤدي الى زيادة في قوة القطع المطلوبة . في هذه الدراسة، ركزنا على تأثير عملية الطلاء على مشاكل تأكل سطح العدة وظهور الحفرة. وسبب ظهور الحفرة هو تدفق الرايش على وجه وسطح العدة . في حين تآكل جناح العدة يحدث بسبب الاتصال بين الاداة وقطعة العمل . ولتقليل من حفر التأكل على سطح العدة , عملنا على تحسين سطح عدة القطع بعملية الطلاء بإضافة نترات الألومنيوم التيتانيوم(AlTiN) باستخدام $Al_{0.67}$ $Ti_{0.33}$ في نظام قوس كاثودي للطلاء.وللحد من تأكل جناح عدة القطع ، يعتبر (AlTiN) ايضا من أفضل المواد لطلاء العدة. تجريبيا بعد اختبار وتشغيل عدة القطع المطلية فقد اثبت ان الطلاء باستخدام AlTiN تعتبر فعالة جدا في الحد من التآكل . حيث كانت نتائج قيم خشونة السطح المطلي بل (AlTiN) بعد عملية التشغيل هي 0.14, 0.15, 0.23, 0.02, 0.21 µm ميكرون بسمك طبقات 1.138, 1.518, 1.735, 2.717, 3.0818 µm على التوالي .اقل معامل احتكاك ظهر عند سمك(2.717µm). علما ان ارتفاع معامل الاحتكاك للطلاء كان نتيجة الخشونة العالية ومساحة الاتصال الواسعة بين الكرة الفولاذية للجهاز ومنطقة الطلاء .واهم العوامل التي استخدمت لقياس حفر التأكل هي العمق وعرض التآكل.