

## PROGRESSION AND WEAR MECHANISM OF CVD CARBIDE TOOLS IN TURNING Ti-6Al-4V ELI

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### ABSTRACT

Wear on the flank of a cutting tool is caused by friction between newly machined surface and the contact area on the tool, which plays predominant role in determining tool life. Detailed study on progression and wear mechanism at the cutting edge of CVD carbide tools were carried out at cutting speed of 55 – 95 m/min, feed rate of 0.15 – 0.35 mm/rev and depth of cut of 0.10 – 0.20 mm. The pattern of wear progression on the flank face of the carbide tools consist of three stages for all the cutting speed tested. Those are; extremely rapid wear at the initial stage, gradually increases at the second stage and rapidly increases at the final stage especially at high depth of cut (0.20 mm) and high feed rate (0.35 mm/rev). High feed rate and depth of cut would cause high temperature generated and consequently damaged the cutting edge. While low depth cut and cutting speed would cause the wear formation near to the nose radius. Machining at low cutting speed (low temperature generated) resulted in titanium alloy welded onto the cutting edge. Wear mechanism such as abrasive and adhesive wear were observed on the flank face. Crater wear due to diffusion was also observed on the rake face.

**Keywords:** wear progression, wear mechanism, CVD inserts, Ti-6Al-4V ELI.

### 1. INTRODUCTION

Titanium and titanium alloys are used extensively in aerospace because of their excellent combination of high specific strength (strength-to-weight ratio), which is maintained at elevated temperature, their fracture resistant characteristics and their exceptional resistance to corrosion at high temperature (Narutaki and Yamane, 1993; Ezugwu and Wang, 1997; Ezugwu et al., 2005). Some typical characteristics of aerospace super alloys are austenitic matrix which promotes rapid work hardening, reactivity with cutting tool materials under atmospheric conditions which tends to build-up-edge and weld onto cutting tools, low thermal conductivity which impairs the surface quality and presence of abrasive carbide in their microstructures (Che Haron, 2001; Ezugwu, 2005). There are several attempts to improve the machinability of titanium

alloys, such as dry machining and using advanced cutting tool materials. 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). Meanwhile, additional coatings on cemented carbide tools are applied in order to improve the tool wear and tool life performance (Ezugwu, 2005). With recent development in advanced cutting tool materials such as coated cemented carbide tool by super hardness materials, the coatings have a potential to improve the machinability of titanium alloys. The coating layers also help to increase the performance of cutting tools, consequently increase the machining productivity (Ezugwu et al., 2003; Che Haron et al., 2007).

Coated cemented carbide tools are suitable for finishing titanium alloys at speed of 75 m/min, feed rate of 0.25 mm/rev. and depth of cut 0.25 mm (Kennametal 2006). Satisfactory tool life and surface finish have been reported when machining titanium alloys. In addition hard coating layer on the cutting tool such as TiN, TiCN and TiAlN will reduce the friction between the cutting tool and work piece material (Kennametal, 2006). Coated cemented carbide tools can be used in dry machining of titanium alloys at lower cutting speeds and relatively lower feed rates. Their application in dry machining of titanium alloys will result in lower cost compared to CBN and ceramic tools. Application of multilayer hard coating on carbide tools in dry machining of titanium alloys have been reported to increase the productivity significantly compared to a single layer or uncoated tools (Jawaid et al., 1999; Ezugwu, 2005).

The contribution of this study is to investigate the performance of tool wear characteristics of coated cemented carbide tool when finish turning a new aerospace material of Ti-6Al-4V ELI under dry machining condition.

### 2. EXPERIMENTAL PROCEDURES

The workpiece material used in the machining trials was a titanium alloy alpha-beta Ti-6Al-4V Extra Low Interstitial (Ti-6Al-4V ELI), which is equiaxed  $\alpha$  phase and surrounded by  $\beta$  in the grain boundary as shown in Figure 1.

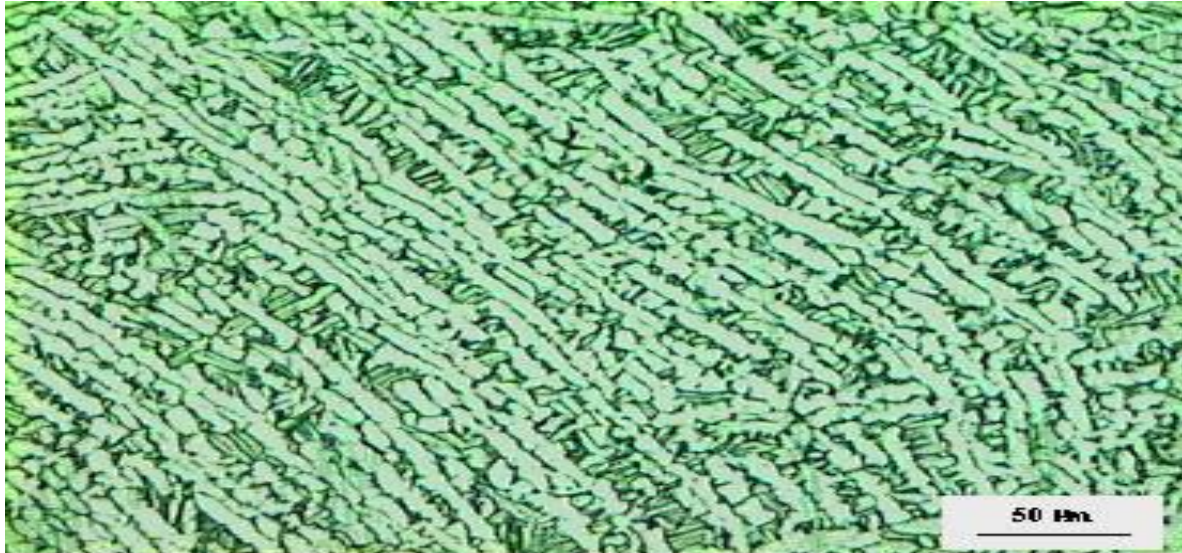


Figure 1. Microstructure of Ti-6Al-4V ELI

Table 1. 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

The chemical composition and physical properties of workpiece material are given in Table 1 and 2, respectively. At least 3 mm of material at the top surface of workpiece was removed in order to eliminate any surface defects and residual stress that can adversely affect the machining result (Kalpakjian and Schmid, 2001).

The machining trials under dry machining condition and high cutting speed were carried out using the

Colchester T4 6000 CNC lathe machine. Tools and tool holders were selected based on the recommendation of the tool supplier (Kennametal, 2006). Chemical Vapor Deposition (CVD) inserts with designation KC9225 (CCMT 12 04 04 LF, ISO designation) were used to turn the titanium alloy Ti-6Al-4V ELI under dry cutting condition. Four layers of coating materials for each insert, which consist of TiN-Al<sub>2</sub>O<sub>3</sub>-TiCN-TiN, were selected. The parameters for turning operation are as shown in Table 3.

Table 2. 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

The average flank wear (*VB*) was measured by using a Mitutoyo Tool Maker Microscope at 20x magnification, and the machining time was recorded using a stopwatch. The wear and the cutting time were recorded at regular interval of one pass turning

operation. The turning process was then stopped when *VB* reached 0.2 mm. The wear and failure mode of inserts were observed under the optical microscope. The detailed investigation of the worn out tool was carried out using Scanning Electron Microscope (SEM).

Table 3. Factors and levels used in the experiment.

Factors	Levels		
	0	1	2
A- Cutting speed (m/min)	55	75	95
B- Feed rate (mm/rev)	0.15	0.25	0.35
C- Depth of cut (mm)	0.10	0.15	0.20

### 3. RESULTS AND DISCUSSION

#### Tool Wear Progression

The progress of flank wear land versus cutting time for turning Ti-6Al-4V ELI using CVD carbide tools at cutting speed of 55, 75 and 95 m/min, at various feed rate and depth of cut are shown in Figures 2, 3 and 4, respectively. It is clearly seen that a typical three-stage pattern of tool wear was obtained, similar pattern was reported by Jawaid et al. (1999) when machining titanium alloy with coated and uncoated carbide tools. The wear occurred rapidly at the initial stage, gradually

increased at the second stage and extremely increased at the final stage. Rapidly increased at the initial stage was due to small contact area between the cutting tool and the workpiece, which caused increased in temperature at the cutting edge, and some material easily removed from the cutting tool (Che Haron, 2001; Gusri et al., 2008). Ibrahim et al. (2007) found that the burn mark appeared on the coating layers of cutting tool when machining titanium alloy with coated carbide tool under dry machining due to high temperature concentration on the cutting edge.

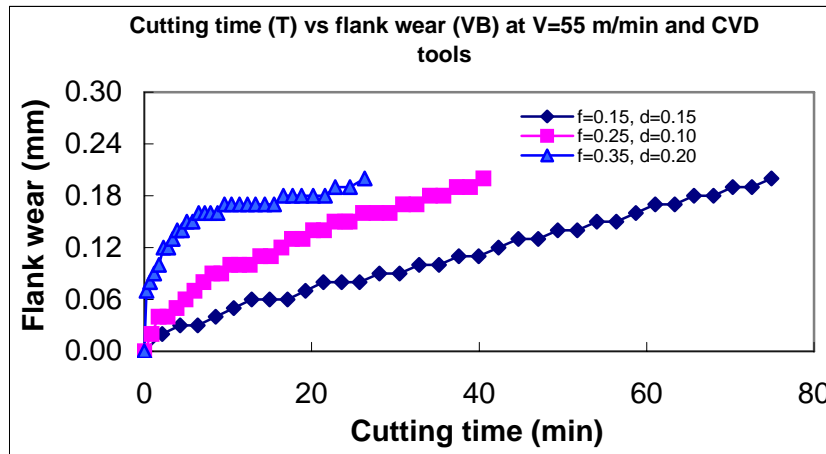


Figure 2. The flank wears progression of cemented carbide tools at cutting speed of 55 m/min.

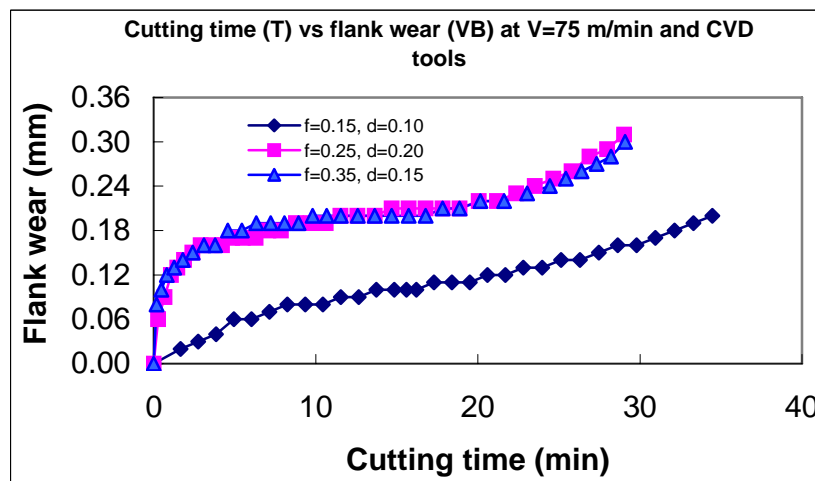


Figure 3. The flank wears progression of cemented carbide tools at cutting speed of 75 m/min

Figure 2 shows the wear progression of the CVD tools at various feed rate and depth of cut, while kept the cutting speed constant at 55 m/min. The tool wear progression at feed rate of 0.35 mm/rev and depth of cut of 0.20 mm shows that at the initial cutting, the wear increases dramatically until the VB reached 0.17 mm due to high feed rate and high depth of cut. The high depth of cut then directly influenced the cutting force due to the large contact area between the cutting

tool and workpiece. Meanwhile, the wear progression at feed rate of 0.15 mm/rev and depth of cut of 0.15 mm has similar pattern to the wear progression at feed rate of 0.25 mm/rev and depth of cut of 0.10 mm. This shows that both feed rate and depth of cut significantly influenced the cutting tool wear progression. Jawaid (2000) found that the feed rate also contributed to increase in temperature during machining titanium alloy. This weakens the cutting tool materials.

Figure 3 shows the wear progression of three types of tools at cutting speed of 75 m/min at various feed rate and depth of cut. The wear progression patterns at feed rate of 0.25 mm/rev and depth of cut of 0.20 mm are similar to that at feed rate of 0.35 mm/rev and depth of cut of 0.15 mm from beginning until end of the tool life. At the initial stage of machining, the wear progression increases rapidly until  $VB$  reached 0.17 mm, followed by gradual increases until  $VB$  reached 0.24 mm. Therefore, the feed rate and depth of cut give similar contribution to the wear. On the other hand, machining at low feed rate (0.15 mm/rev) and low the depth of cut (0.10 mm) produced slow wear progression. Machining titanium at low depth of cut produced low cutting force, which also affected the

wear progression of titanium alloys (Trent, 1995; Ezugwu et al., 2003). They also found that operating at low depth of cut and low cutting speed, can caused chips stick on the cutting edge and wear occurred at nose radius, predominantly.

Figure 4 shows that the wear progression patterns on the cutting edge at cutting speed of 95 m/min, at various feed rate and depth of cut are similar. Variation of machining parameters, high feed rate and low depth of cut, or low feed rate and high depth of cut, gives similar contribution on the wear progression of the cutting tools. At the initial machining stage, the wear increases rapidly until  $VB$  reached 0.11 mm.

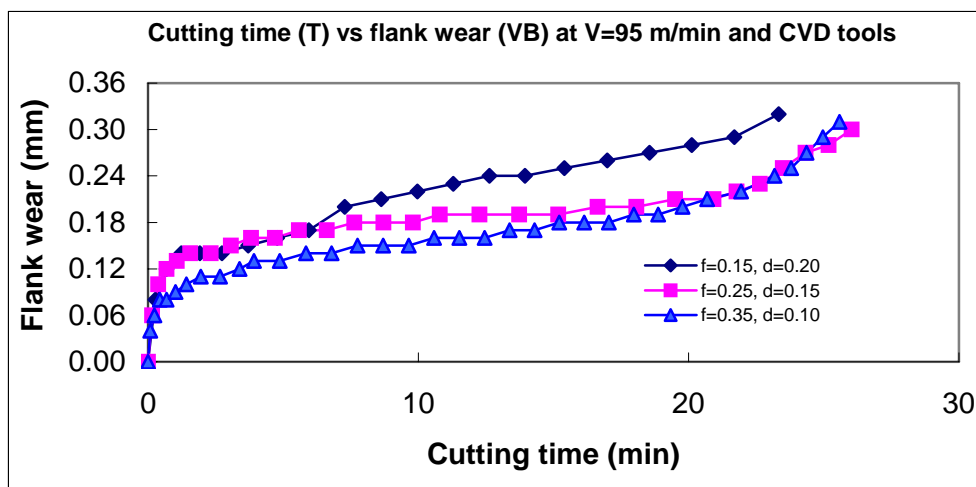


Figure 4. The flank wears progression of cemented carbide tools at cutting speed of 95 m/min

Figures 5 shows a flank wear progression stage at the initial machining when cutting speed of 55 m/min, feed rate of 0.15 mm/rev and depth of cut of 0.15 mm. At the first stage, the wear increases rapidly to the  $VB = 0.087$  mm. When the  $VB$  reached 0.087 mm or the cutting time of 1 min and 8.10 sec., there is a chip that welded at the cutting edge of the tool. Next, the chip is removed away but some material of titanium alloy is still remained at the cutting edge. Later, more titanium alloy adhered on the cutting edge and looked like a build-up-edge. When the flank wear of the cutting tool reached 0.105 mm or the cutting time of 3 min and 24.20 sec, more titanium alloy welded at the cutting edge. Further machining, caused the welded titanium alloy to be removed from the cutting edge. With further machining severe wear was observed after machining more than 6 min when  $VB$  reached 0.115 mm. This condition was found at  $VB$  of 0.115 mm or at the cutting time of 6 min and 49.85 sec. The welded titanium occurred at the cutting edge of tool because of the cutting process operated at low cutting speed (55 m/min). Similar to the finding from previous researcher that operating at low cutting speed and low depth of cut, caused chips stick on the cutting edge (Ezugwu et al., 2003). Operating at low cutting speed generates a low temperature between the cutting tool and chip, so

that this temperature is not high enough to release chip from the cutting edge, as shown in Figure 5 at stage 2. Che Haron et al. (2007) and Venugopal et al. (2007) reported that there was a strong bonding between the chip and tool material. When high temperature was generated, this condition was conducive for adhesive wear, therefore rougher machined surface will produced.

The accumulated adhered or welded titanium on the rake face of the cutting tool and the cutting edge prevent the chip from direct contact with the tool. Most commonly occurs at intermediate cutting speed and extremely low feed rate (Trent, 1991). At shown in Figure 5 at stage 6, the welded titanium removed from the tool after 5 min and 40.25 sec of cutting. Some material of tool also was probably removed which lead to the initiation of chipping at the cutting edge. Similar phenomena to Figure 5, Figure 6 shows a flank wear progression steps at the second area of machining when machining at cutting speed of 75 m/min, feed rate of 0.15 mm/rev and depth of cut of 0.10 mm. Some material of titanium alloy adhered or welded on the rake face and the cutting edge of tool. Small amount of titanium alloy is welded on the cutting edge when  $VB$  reached 0.162 mm. Further machining caused more



work material deposited on the flank and rake face of the cutting tool. Then, the adhered or welded titanium alloy was removed from the cutting tool. As shown in Figure 6, the adhered or welded titanium alloy is at the nose radius whereas in Figure 5 the adhered or welded titanium alloy is at the flank face. It was probably due

to the effect of cutting speed, which generates temperature on the cutting edge during the machining process. According to König (1979) the adhered or welded workpiece material on the cutting tool occurred when machining titanium alloy due to low generated temperature when machining at the low cutting speed.



Figure 5. The flank wear progression steps at the initial machining when cutting speed of 55 m/min, feed rate of 0.15 mm/rev and depth of cut of 0.15 mm.

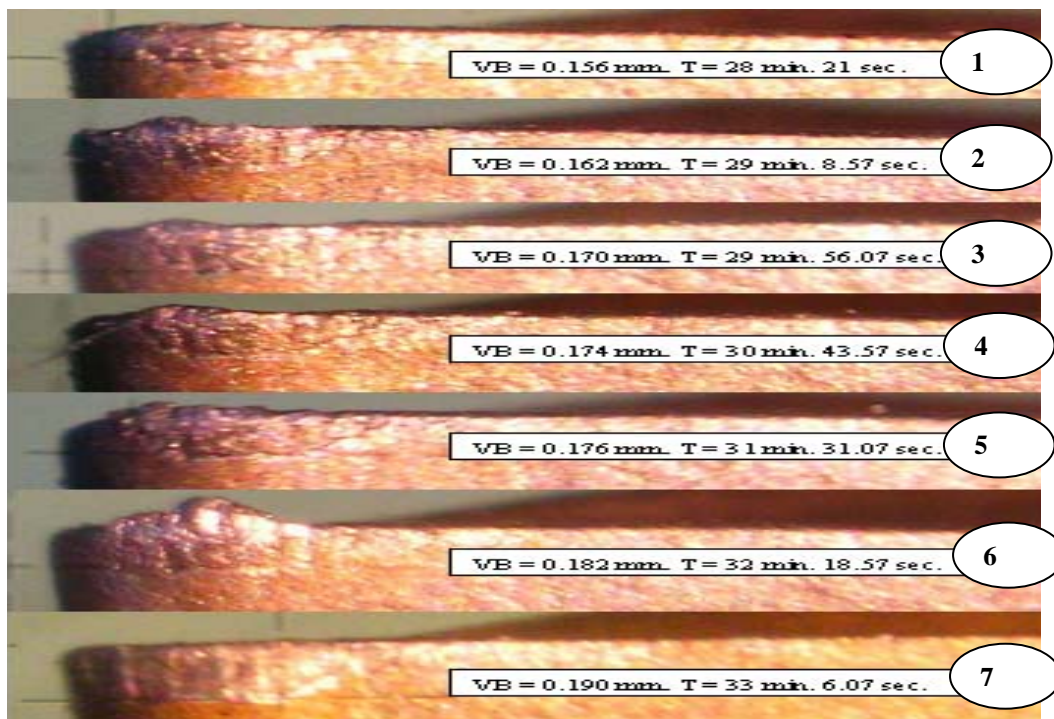


Figure 6. The flank wear progression steps at the second area of machining when cutting speed of 75 m/min, feed rate of 0.15 mm/rev and depth of cut of 0.10 mm.

## Wear Mechanism

Figure 7 shows the flank wear, crater wear and chip welded on the cutting edge near the nose radius, when machining titanium alloy at cutting speed of 55 m/min, feed rate of 0.25 mm/rev and depth of cut of 0.10 mm. The flank wear occurred near to the nose radius was

due to low depth of cut. The low depth of cut caused a small contact area between cutting tool and workpiece material. Turning at low cutting speed, will generate low temperature. Ginting and Nouari (2006) confirmed that the dominant tool wear of uncoated and coated tool was localized flank wear.

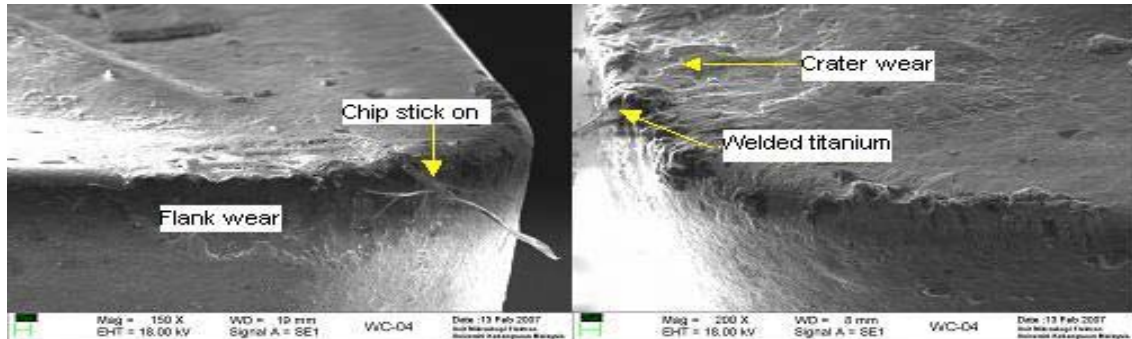


Figure 7. SEM micrograph shows the flank wear, crater wear and chip stick on cutting edge of CVD coated insert at  $v = 55$  m/min,  $f = 0.25$  mm/rev.,  $d = 0.10$  mm and Cutting Time = 24,53 min.

Abrasive and adhesive wear which occurred at the cutting speed of 95 m/min, feed rate of 0.35 mm/rev and depth of cut of 0.20 mm are shown in Figure 8. The wear increases with cutting speed owing to increase in the slip distance and cutting temperature during machining. Adhesion or welding of titanium alloy onto the flank and rake faces were also observed. Adhesion of titanium alloy can be seen clearly, which is demonstrating a strong bond (no evidence of any

gaps) at the workpiece-tool interface. According to Konig (1979), the adhesion wear took place after the coating had worn out or coating delamination had been occurred. The adhered or welded titanium will be swept away by the tool, and deposited on to the workpiece continuously, thus leading to the initiation of chipping, flaking and finally caused the breakage of the carbide at the cutting edge.

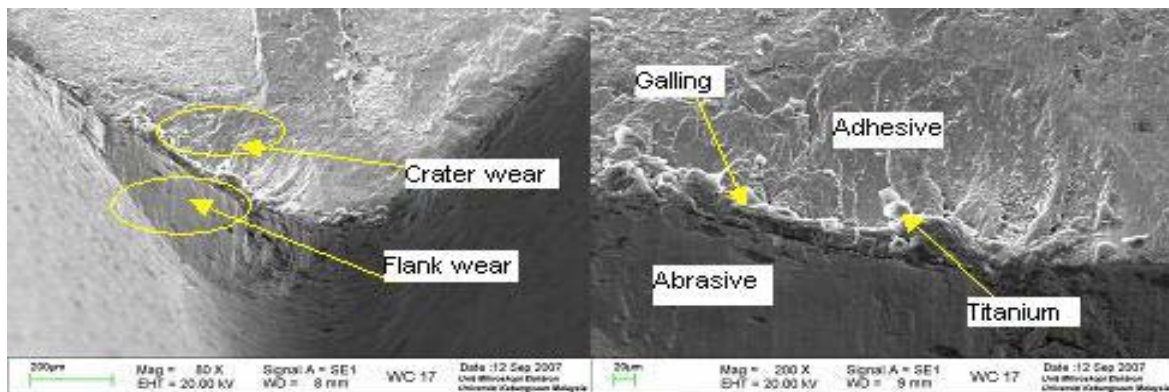


Figure 8. SEM Micrograph Shows Types of wears Titanium on Cutting Edge of CVD Coated Insert at  $v = 95$  m/min,  $f = 0.35$  mm/rev.,  $d = 0.20$  mm and Cutting time = 20, 15 min.

## 4. CONCLUSIONS

From the analysis of the wear characteristics of CVD coated cemented carbide tools, the following can be concluded.

1. The pattern of wear progression on the flank face of the carbide tools consist of extremely rapid wear at the initial stage, gradually increases at the second stage and rapidly increases at the final stage.

2. The feed rate and depth of cut are significantly contributed to the generated temperature and consequently damaged the cutting edge.
3. Low depth cut and cutting speed would cause the wear formation near to the nose radius. Machining at low cutting speed (low temperature generated) resulted in titanium alloy welded onto the cutting edge.
4. Adhesion or welding of titanium alloy onto the flank and rake faces demonstrated a strong bond at the workpiece-tool interface. The adhesion wear took place after the coating had worn out or coating delamination had been occurred.

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