PERFORMANCE OF NANO-COMPOSITE TiAlN AND Si_3N_4 COATED CEMENTED CARBIDE TOOLS WHEN TURNING Ti-6Al-4V ALLOY UNDER HIGH-PRESSURE COOLANT SUPPLY

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Abstract. *The performance of recently developed nano-composite (TiAlN and* Si_3N_4*) coated cemented carbide tools when machining commercially available titanium Ti-6Al-4V alloy at high-speed conditions was investigated. Machining was conducted using emulsion cutting fluid supplied under conventional flow and at high-pressures of 7 and 11 MPa. Comparative trials using uncoated cemented carbide were also conducted. Tool wear and surface roughness were monitored during the machining trials. The nano-composite inserts performed poorly relative to the uncoated cemented carbide tools. The reactivity of the titanium work material and the nano-coating could be responsible for the poor performance due to higher wear rates. Flank wear was the dominant failure mode. Increase in coolant pressure, from conventional flow to 7 MPa, improve tool life due to improved cooling and lubrication at the cutting interfaces. Adhesion of the work material followed by plastic flow and abrasion are the mechanisms responsible for wear of the nano-composite coated tools.*

Keywords: *Nano-composite coating, Ti-6Al-4V, High-pressure coolant supply, Tool life, Wear mechanisms.*

1. INTRODUCTION

The aerospace market, in the last decade, increase largely, graces the insertion of new manufacturers in the global scenario that resulted in a better and larger competition.

Titanium and its alloys are used predominantly in the aerospace industry due to their combination of superior properties including high specific strength that are maintained at elevated temperature conditions. Titanium alloys exhibit exceptional resistance to corrosion, which provide savings on protective coating like paints that will otherwise be used in the case of steel. Complex titanium alloy components are produced by conventional machining processes such as turning, milling, drilling, boring, etc. Most studies on the machining of titanium-based alloys have described chip formation and its control, recommended cutting tool materials and their wear mechanisms (Komanduri et al., 1981; Ezugwu and Wang, 1997; Barry et al., 2001; Ezugwu et al., 2003; Ezugwu et al., 2005). Titanium alloys are classified as difficult-to-cut materials. This is because they are very expensive to machine relative to other materials like cast iron and steels. Machining of titanium alloys is hindered by the severe tribological conditions that occur at the cutting interfaces resulting to high chip-tool interface temperature, accelerated tool wear, poor dimensional tolerance, poor surface finish, high power consumption and cutting forces, vibration, acoustic emission, etc.

Nand et al. (2009) found no tool material that was sufficiently chemically stable to exhibit low wear rates by virtue of their low solubility in titanium. The elastic modulus of titanium and its alloys is around of 110 GPa (while that of steel is 207 GPa). When titanium alloys are subjected to cutting forces they tend to deflect twice as much as that of steel with consequent greater spring back effect on the flank surface of the cutting tool. This leads to chatter mark on the workpiece surface and enhanced flank wear of the cutting tool.

According to Nand et al. (2009), in machining of titanium alloys, chips are formed by catastrophic shear failure due to the onset of plastic instability and strain localization in narrow shear bands. Such as the chip formation mechanism leads to high dynamic cutting forces and high secondary shear zone temperature responsible for rapid chemical reaction between the chip and the tool with rapid wear of the cutting tool (Kaminski and Alvelid, 2000).

The availability of advanced cutting tool materials such as coated and uncoated carbides, cermets, ceramics, Polycrystalline Diamond (PCD) and Polycrystalline Cubic Boron Nitride (PCBN), have significantly improved the machinability of titanium alloys. In addition, efficient cooling techniques such as high-pressure coolant supplies are employed to provide dual functions of improving tool life and efficient chip segmentation during machining (Ezugwu et al., 1990; Ezugwu and Bonney, 2005).

Coating is applied to the tool substrate in order to improve their physical and/or mechanical properties (Ezugwu et al., 2005). Coating techniques usually employed in the manufacturing industry include chemical vapour deposition (CVD), physical vapour deposition (PVD), electroplating, plasma spraying, diffusion treatment and slat baths (Tjong and Chen, 2004). CVD and PVD coating processes are the most common methods for coating cutting tool materials.

Coating materials frequently used, singly or jointly, for machining applications are Al_2O_3, TiN, TiC, TiCN, TiAlN, CrN, TiZrN and TiB_2.

The recent developments of the nano-materials enabled a better application of the usual coating materials previously cited in the machining tools.

Tjong and Chen (2004) reported that the developments of nano-materials are on the increase in recent years due to their existing and/or potential applications in a wide variety of technological areas. Nano-coatings with grain sizes in nanometer range (below 10 nm) have excellent strength, hardness and toughness, which are requirements for cutting tool materials (Tjong and Chen, 2004; Veprek et al., 1998; Zhang et al., 2003; He and Schoenung, 2002). Nano-composite coatings have structures with thickness in the nanometer range. In the multilayered structures (generally obtained by deposition of a large number of the individual layer) no dislocation source could operate within the layers. Another structure is formed from single layer nano-composite coatings with microstructures comprising of crystallites, embedded in an amorphous matrix. The softening of the coating is prevented by blocking grain boundary sliding (Ezugwu and Bonney, 2005). Frequently these nano-composites have hardness above 40 GPa (Tjong and Chen, 2004; Veprek et al., 1998). The nanocomposite coatings could be classified as hard (above 20 GPa), super-hard (above 40 GPa) or ultra-hard (above 80 GPa) depending on coating properties required (Zhang et al., 2003). From the machining perspective, development of nano-coatings could be considered very relevant as the improved properties must be expected to drastically reduce machining costs.

Ezugwu and Wang (1997) reported that about 80% of the heat generated in cutting remains in the tool and only about 20% of heat is carried away by the chip, while in machining of steels only about 50–60% of the heat generated is retained by the tool. Thus the tools employed in machining of titanium alloys are subjected to higher temperatures. Furthermore, the chips produced are thin and also the chip–tool contact length is very small (it is about one third that of steel). More over titanium alloys can retain high strength even up to 800 ˚C temperature and as such can resist deformation at elevated temperature. As a result, the cutting stresses on tools are very high and occur very close to the cutting edge of the tool (Ezugwu and Wang, 1997). The temperature distribution pattern shows that the heat-affected zone is small and meets the cutting edge radius (Smart and Trent, 1975).

According to Klocke and Eisenblätter (1997), coolant has a direct influence on the manufacturing economics. Therefore, by abandoning conventional cooling and using dry or high pressure coolant (HPC) assisted machining, the cost related to the use of coolant can be reduced. Weinert et al. (2004) have shown that besides an improvement in the economic efficiency of the machining process, dry machining principles can also contribute to the health of machine tool operators and environment concerns.

2. EXPERIMENTAL PROCEDURES

The workpiece is Ti-6Al-4V bar, 300 mm long and 200 mm diameter. The machining trials were carried out on a CNC lathe, with an 11 kW motor drive delivering a maximum torque of 1411 Nm. The high-pressure coolant delivery system has a power of 30 HP, a maximum flow rate of 93.6 l/min and maximum pressure of 21 MPa. An emulsion cutting fluid with a high lubricity and cooling capacity was used for the machining trials.

Tool wear was measured with an optical microscope at a magnification of 25X. Tool materials used were uncoated and nano-composite (TiAlN and Si_3N_4) coated cemented carbide tools. The coating consists of nano-crystalline grains of TiAlN embedded in an amorphous matrix of Si_3N_4. A multilayer coating of TiAlN is first deposited followed by a nano-composite layer at the surface. This produces a layer with thickness of 1 to 4 μm, nano hardness of 4500 HV, friction coefficient (relative to steel) of 0.45 and maximum decomposition temperature of 1200 °C. The substrates of the cemented carbide inserts investigated are similar and their composition are given in Table 1.

Tab. 1 – Physical properties and chemical composition of cemented carbide tools (ISO K10 grade).

Hardness (Vickers HV)	Density (g.cm-3)	Substrate grain size (μm)	Composition (wt. %)		
			WC	(Ta, Nb)C	Co
1760	14.95	1.0	93.8	0.2	6

The inserts were used to machine the titanium alloy at the following cutting conditions:

Cutting speeds (v_c): 110, 120, 150 and 200 m/min;
Feed rate (f): 0.15 mm/rev;
Depth of cut (doc): 0.5 and 3 mm.

The machining trials were carried out under conventional coolant flow and coolant pressures of 7 MPa (70 bar) and 11 MPa (110 bar). The coolant concentration was 6%.

Tool rejection criteria stipulated for the machining trials are:

Maximum flank wear, VBmax = 0.4 mm;
Nose wear, VC = 0.4 mm;
Notch wear, VN = 0.6 mm;
Surface roughness, Ra = 1.6 μm;
Fracture or catastrophic failure of the cutting tool.

The rejection criteria are typical of those employed in finish machining. The worn inserts were observed in the scanning electron microscope (SEM). Analyses of the micrographs help to identify the tool failure mode(s) and the mechanism(s) responsible for tool failure.

3. RESULTS AND DISCUSSIONS

3.1. Tool life

Figure 1 shows maximum flank wear recorded when machining Ti-6Al-4V for 2 minutes with the uncoated and nano-composite coated carbide inserts under roughing conditions (f = 0.15 mm/rev, doc = 3 mm and v_c = 120 m/min) using conventional coolant supply. Higher tool wear was recorded with the nanocoated tool, 52.8% higher than the uncoated carbide.

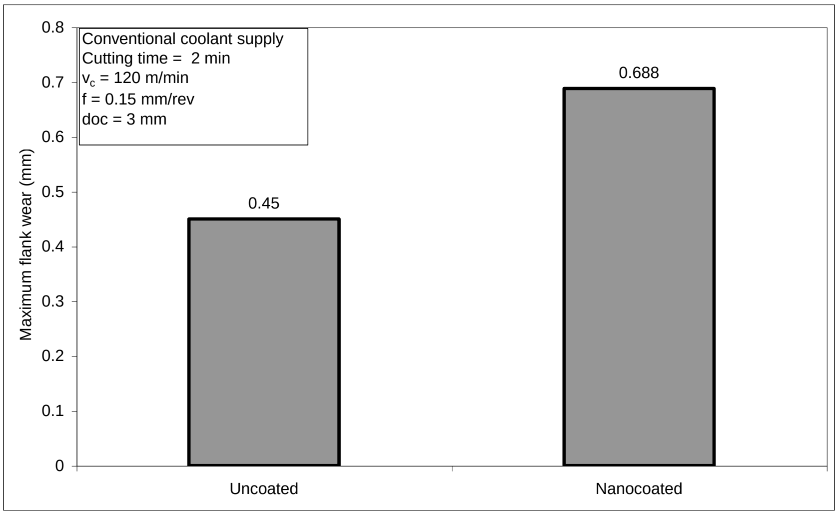


Fig. 1 – Comparative results of uncoated and nano-coated carbide inserts under roughing conditions using conventional coolant flow.

Much longer tool life was recorded when machining with uncoated and nanocoated cemented carbide tools at high-pressure coolant supply (11 MPa) as illustrated in Fig. 3 if compared with the machining using conventional coolant flow (Fig. 2). There was, however, a substantial reduction in tool life when machining Ti-6Al-4V alloy with nanocoated cemented carbide tools relative to uncoated cemented carbide under high-pressure coolant supplies of 11 MPa. It is anticipated that the coatings will minimise tool wear rate and consequently increase tool life, but this depends on the tribosystem evaluated. Although the nanocoated inserts have higher mechanical properties, elements like Al, Ti and N present in its matrix have higher chemical affinity with Ti, Al and V in work material and will therefore encourage higher tool wear rate, thus lowering tool life.

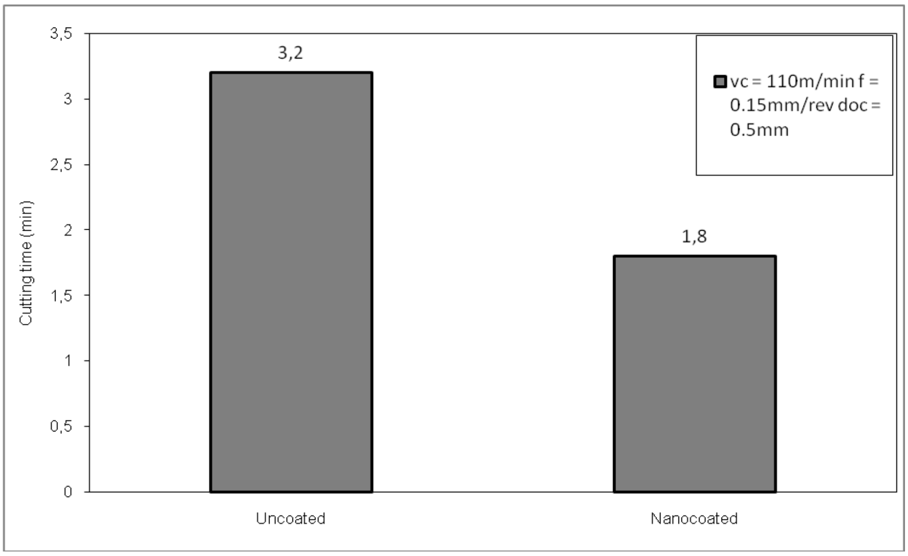


Fig. 2 - Comparative results of uncoated and nanocoated carbide inserts using conventional coolant flow.

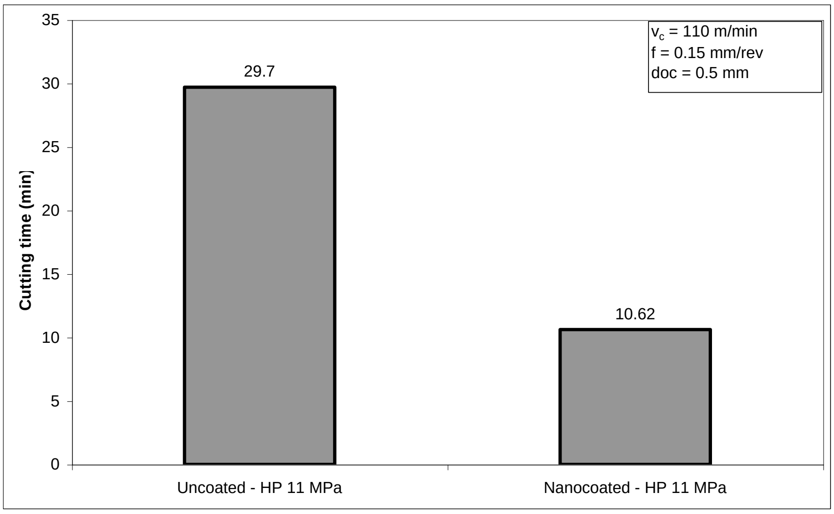


Fig. 3 – Comparative results of uncoated and nanocoated carbide inserts using high pressure coolant flow.

3.2. Tool life and surface roughness of the nanocoated cemented carbide tools

Results of the machining trials under high-pressure coolant supply (11 MPa) at different cutting speeds (110, 150 and 200 m/min) are shown in Figure 4. Increases in cutting speed rapidly increase flank wear, hence lowering tool life as a result of increased heat generation at the chip-tool and tool-workpiece interfaces (Trent and Wright, 2000). Moreover, the thin nanocoated layer is easily worn due to high chemical affinity between the work material and the coating elements. It can also be seen in Figure 3 that maximum flank wear of 0.25 mm (250 μm) was recorded after machining at a speed of 110 m/min for 1 minute. The recorded flank wear remained fairly constant with prolonged machining up to 6 minutes. Further machining resulted to appreciable increase in the maximum flank wear. Machining at speeds in excess of 110 m/min led to higher flank wear rates and associated reduction in recorded tool life.

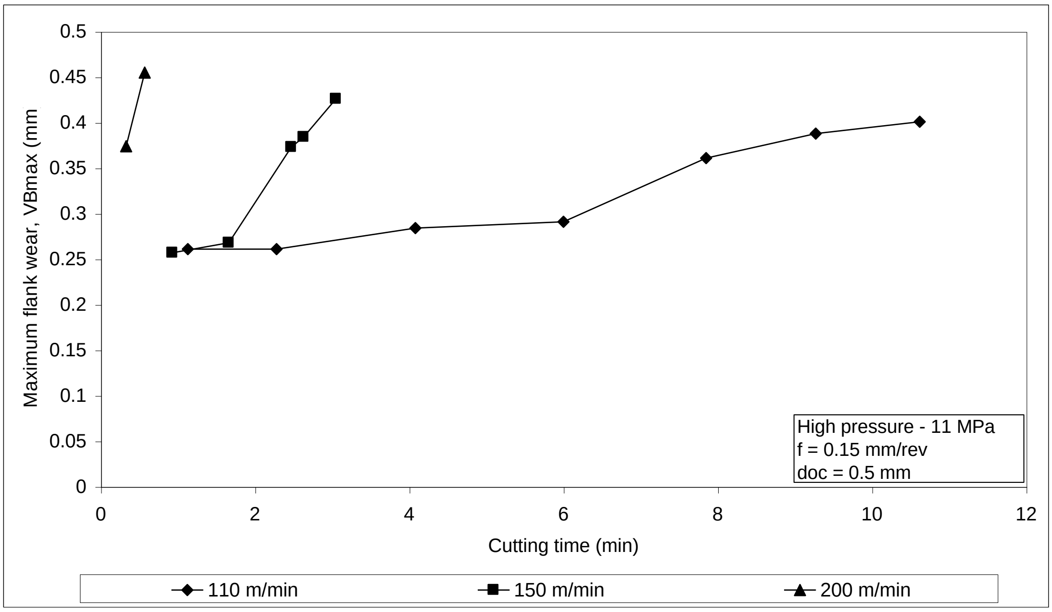


Fig. 4 – Flank wear curves obtained when machining with nanocoated carbide tools at 11 MPa coolant supply.

Figure 5 shows the variation of VBmax with cutting time when machining Ti-6Al-4V at a higher cutting speed of 150 m/min, feed rate of 0.15 mm/rev and depth of cut of 0.5 mm under various coolant supply conditions.

Increases in the coolant pressure from 7 MPa to 11 MPa increase the flank wear rate, consequently lowering tool life. Sharma et al (1971) reported that exchange of heat at the cutting interfaces during machining is enhanced under high coolant pressures than with conventional coolant flow, hence temperature at the cutting zone is reduced significantly. It can also be observed that the least wear rates were recorded when machining under high-pressure coolant supply of 7 MPa. The better coolant pressure evaluated when machining at a cutting speed of 150 m/min, feed rate of 0.5 mm/rev and depth of cut of 0.5 mm is therefore 7 MPa.

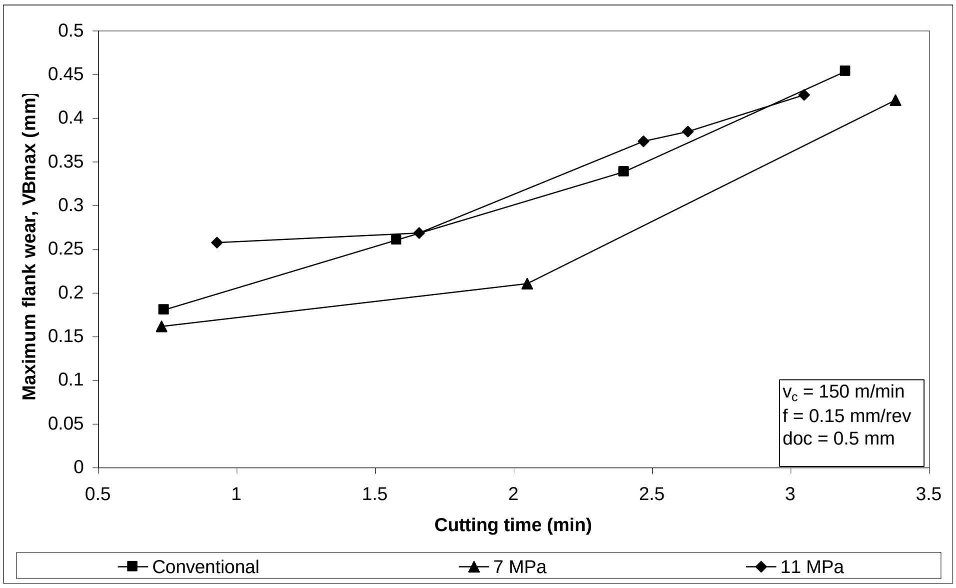


Fig. 5 – Flank wear curves when machining with nanocoated inserts at different coolant pressures.

The surface roughness values recorded at various speed conditions were well within the rejection criteria of 1.6 μm (Figure 6). The surface roughness generated when machining at a speed of 110 m/min varies marginally with prolongs machining. In the speed of 150m/min see that the roughness (Ra) generated varied, decrease in the first moment, presumably because of the instability of the tool-holder system. After this, the roughness increase pursues the tendency of the tool wear and decrease in the ends of the acquisitions presumably because of the end of the coating layer.

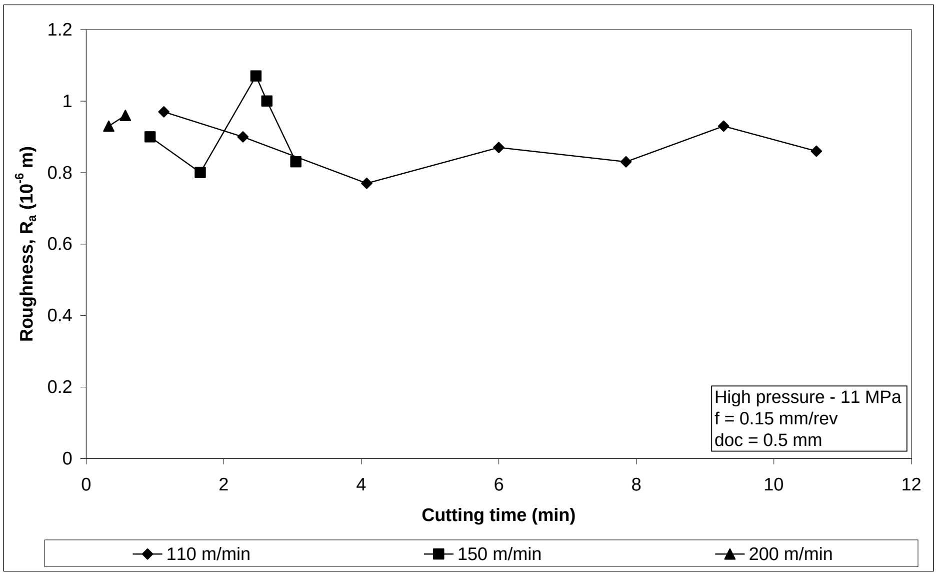


Fig. 6 – Surface roughness (R_a) values obtained when machining at different cutting speeds under 11 MPa coolant supply pressure.

Figure 7 shows variation of surface roughness (Ra) values with cutting when machining under conventional and high-pressure (7 and 11 MPa) coolant supplies. The best surface roughness values were recorded when machining with 7 MPa coolant supply.

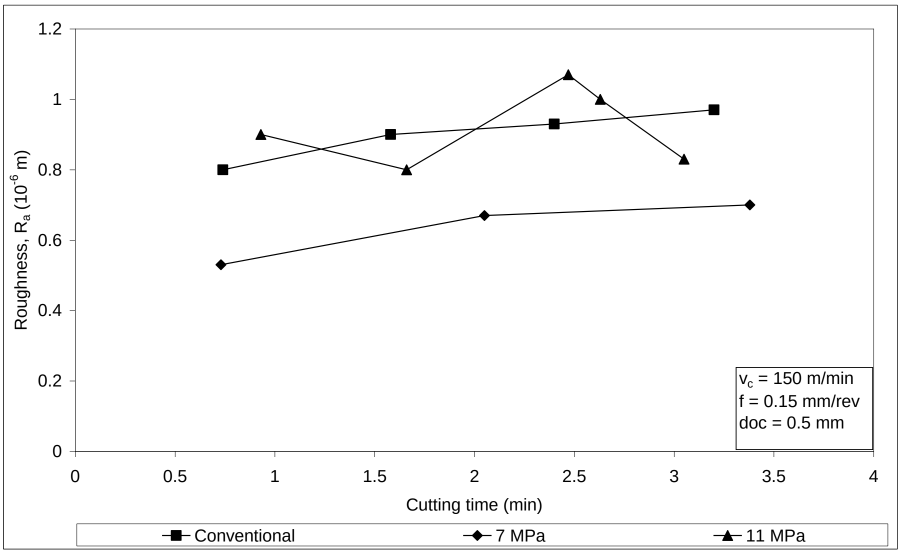
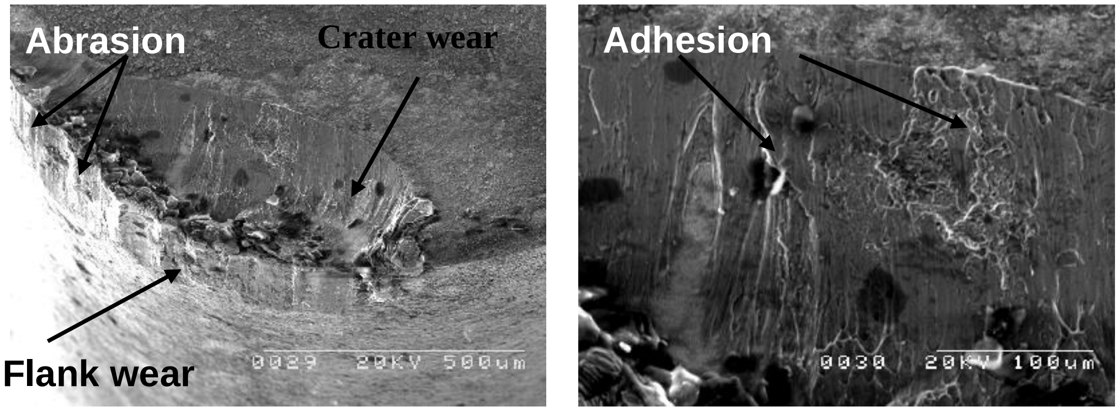


Fig. 7 – Surface roughness (R_a) values when machining at different coolant pressures.

According to Trent and Wright (2000) there are two distinct zones at the chip-tool interface: seizure and sliding zones. The seizure zone is inaccessible by the coolant under conventional flow. Under high-pressure coolant supply, access can be significantly improved, thus enhancing lubricity as well as reducing the friction coefficient and consequently heat generation (Sharma et al., 1971; Ezugwu et al., 2005). Additionally, heat exchange at the cutting interface is improved as well as the tendency to minimise tool wear and improve the surface quality of machined components.

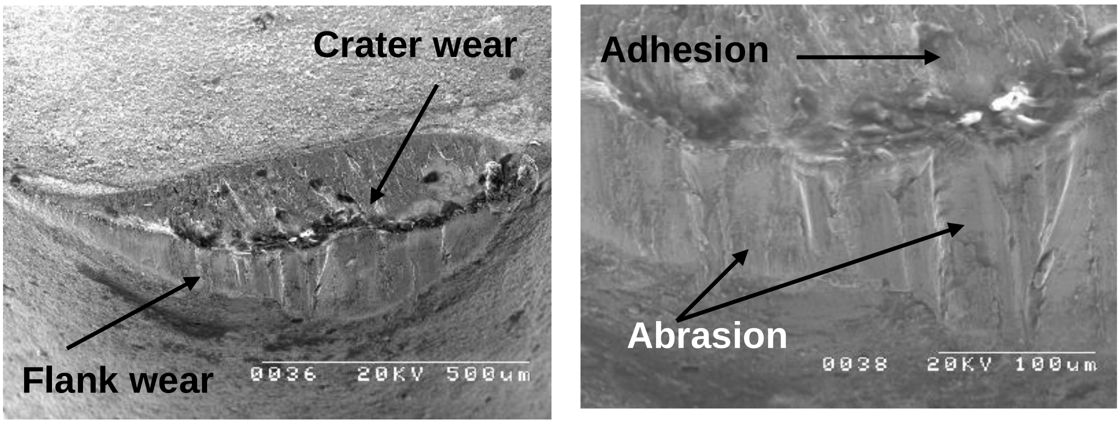
3.3. Effect of coolant application method on tool wear when machining with the nanocoated cemented carbide

Figures 8 and 9 show SEM micrographs of worn tools after machining at a speed of v_c = 150 m/min, a feed of f = 0.15 mm/rev, a depth of cut of doc = 0.5 mm using conventional and 7 MPa coolant supplies respectively. It can be seen that flank and crater wears were the dominant wear modes when machining Ti-6Al-4V alloy with the nanocoated cemented carbide tools. Comparisons of the crater wears suggest that less severe cratering occurred when machining at 7 MPa coolant pressure.



a) General view. b) Detail of the rake face.

Fig. 8 – Worn tool after machining with conventional coolant supply.



a) General view. b) Detail of the flank face and cutting edge.

Fig. 9 - Worn tool after machining with 7 MPa coolant supply.

This is due to the ability of the high-pressure cooling jet to change the chip flow direction on the rake face as a result of a coolant wedge between the chip and the tool rake face. This also improves lubrication and cooling at the cutting interface, consequently reducing the crater depth.

Evidence of adhesion of work material on the worn tools as well as plastic flow and abrasion wear can also be observed in Figures 8 and 9. Adhesion is due to high chemical affinity between the work material and the nanocoating and/or substrate material in addition to the high chip-tool interface temperature encountered when machining Ti-6Al-4V alloys [2, 4, 5]. On the other hand, abrasion wear could be promoted by different hardness of the α and β phases in the Ti-6Al-4V alloy.

3.4. Influence of the cutting speed on tool wear of the nanocoated cemented carbide inserts

Figures 9 and 10 are micrographs of worn tools after machining with conventional coolant flow cutting speeds of 110 and 200 m/min, respectively. It is apparent that the adhesion, plastic flow and abrasion are more pronounced at a higher speed of 200 m/min relative to 110 m/min. This can be associated to the higher chip-tool interface temperature generated when machining at 200 m/min in addition to the increased chemical affinity between the work material, the coating and the tool substrate.

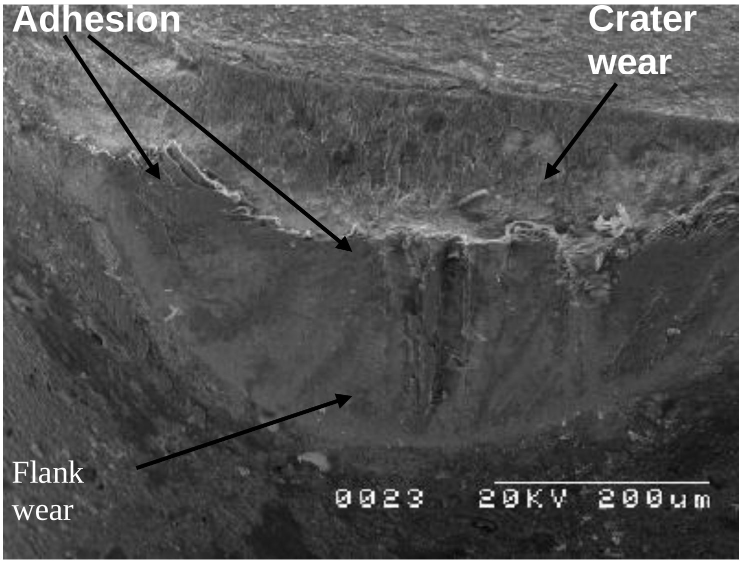


Fig. 10 - Worn tool after machined at a speed of 110 m/min.

4. CONCLUSIONS

The nano-composite TiAlN and Si_3N_4 coated cemented carbide tools gave poor performance relative to uncoated cemented carbide tools, when turning Ti-6Al-4V alloy under conventional and high-pressure coolant supplies at the cutting conditions investigated. The constituent elements (Al, Ti and N) of the nano-composite coated carbide tools have a high chemical affinity with Ti, Al and V from work material, hence decomposition of the coating is accelerated resulting to lower tool life.

Flank and crater wears were the dominant tool failure modes when machining Ti-6Al-4V alloy with the nanocoated cemented carbide tools. The crater wear rate is less severe than the flank wear rate.

Increase in the coolant pressure from conventional flow to 7 MPa pressure gave enhances tool life and surface roughness. Further increase in coolant pressure to 11 MPa increased the flank wear rate, thus lowering tool life. Increase in the cutting speed drastically lowered tool life due to drastically increase in the temperature at the chip-tool and tool-workpiece interfaces.

Adhesion of the work material followed by plastic flow and slight abrasion are the mechanisms responsible for the wear of the nano-composite carbide tools investigated.

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