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Machining and Tribological Characterisation of Uncoated and Coated Carbide Inserts while Turning Tungsten Heavy Alloy

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ABSTRACT

Tungsten heavy alloys are high density alloys containing 80 to 98 wt. % tungsten and a matrix made of relatively low melting elements such as copper, nickel and iron. These alloys are used as radiation shields, CG adjusters and also in armour piercing ammunition. These components essentially require machining to achieve the closer tolerance and finish. However, machining WHAs is challenging as it causes frequent cutting tool failure and surface damage. Hence, there is a need to come up with an appropriate selection of cutting tools and optimum cutting conditions that lead to economic and successful machining of WHAs. However, it is observed that the suitability of different grades of carbide inserts for machining WHAs are least explored. The present work, thus, focuses on the detailed study on three different commercially available cemented carbide inserts during turning operations of WHAs under both dry and wet cutting conditions. Three different feed rates have been used at a constant depth of cut and cutting speed. The best possible cemented carbide tooling solution for machining tungsten heavy alloys has been determined based on the surface finish obtained, chip geometry, cutting forces, and machining temperature. The observations made during machining are correlated to the tribological behavior of the inserts and the alloy from pin-on disc tests. Coated cemented carbide inserts provided surface roughness values lower than 1 µm under finish turning conditions. On the other hand, PVD coated inserts gave consistently better results over different feed rates and are found to experience lower tool wear for the specific cutting conditions. Additionally, an analytical model is used to predict the tool life under the given cutting conditions. The tool wear model also suggested better tool life for the PVD coated insert.

Keywords: Tungsten heavy alloy; Machinability; Cemented carbide insert

NOMENCLATURE

CVD	Chemical Vapour Deposition
PVD	Physical Vapour Deposition
V_B	Wear land measurement, µm
α	Relief angle, radian
γ	Rake angle, radian
v_c	Cutting velocity, m/s
a_w	Width of cut, mm
F_t	Time-dependent thrust force, N
t	Time, min
Z	Temperature dependent tool hardness
F_{ti}	Initial thrust force for a single pass, N
θ_f	Cutting temperature, ^{0}C
θ_{fi}	Initial cutting temperature for a single pass, ^{0}C
$\Delta\theta_{At}$	Average temperature rise, ^{0}C
Q	Primary shear deformation zone heat generation, W
l_c	Tool flank and workpiece contact length, mm
k_w	Workpiece thermal conductivity, W/mK
S_{ei}	Endurance limit, MPa
P_{ei}	Peclet number
f	Uncut chip thickness, mm
ζ	Cutting ratio
ρ	Density of the workpiece, kg/m^3
c_p	Specific heat , J/kgK
W_{sp}	Specific wear rate of the pin, mm^3/N-m
ΔW	Measured loss in weight of the pin, g
ρ_p	Pin material density, g/mm^3
F	Normal load applied during pin- on-disc test, N
L	Sliding distance, m

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1. INTRODUCTION

Tungsten heavy alloys (WHAs) are extensively used as radiation shields, counter balance weights, and damping devices. These alloys are also used extensively as kinetic energy penetrators in anti-tank ammunition. Superior combination of mechanical and physical properties of these alloys makes them suitable for both civilian and defence applications.[1–3] High hardness and strength of tungsten particles surrounded by a relatively ductile matrix requires higher cutting force and hence leads to increase in operating temperature, poor surface finish and intense tool wear. Since surface quality and tool wear are crucial in terms of performance of components and machining costs, respectively, proper selection of cutting tool is of paramount importance. Suzuki *et al.*[4] used elliptical vibration cutting in tungsten alloy mould production and achieved surface roughness to the level of 40 - 100 nm. However, as compared to traditional machining, material removal rate has been compromised.

Sagar, *et al.*[5–7] used uncoated cemented carbide inserts to investigate the tool wear rate and the effect of tungsten content on various machining outputs while turning WHAs. Nandam *et al.*[8] used carbide tooling under cryogenic conditions. Carbide inserts provided satisfactory results in all cases and cryogenic conditions drastically increased the material removal rate. However, no comparison on different grades of tooling have been performed. Extensive studies are available on performance comparison of different tooling for other difficult to machine materials such as Nimonic C-263, Incoloy 825, single-phase tungsten and so on.[9–11] Initial machinability studies on WHA suggested response conditions of forces, temperature and chip formation occurring similar to these materials. Use of coated inserts under normal conditions can produce better surface finish than the results observed under cryogenic conditions. Tool life of uncoated carbide tool, coated carbide and cermet tools were compared in turning of 95WHA under fine finishing conditions and TiAlN coated carbide tool was found to be suitable tool among the ones considered.[12] However, the selected ranges of feed and depth of cut explored were in micrometer level. The observations on the mechanism of tool wear were in line with Sagar *et al.*[6] Davim *et al.*[13] observed that uncoated carbide tools outperformed polycrystalline diamond and CVD diamond tools in dry machining of copper-tungsten alloy. But performance of coated carbide tools in similar conditions for WHAs are yet to be explored.

From the available results, it is evident that suitability of different grades of carbide inserts for machining WHAs are least explored, especially, for production of components like kinetic energy penetrators. Also, tribological properties of the coated tools are hardly correlated with their performance while machining WHAs. Hence, the present work focuses on the much needed investigation that aims to assess the machining performance of three different grades of cutting tool inserts for machining WHAs. Furthermore, pin-on-disc tests have been carried out to understand the tribological behaviour of the selected cutting tools and relate the same with machining performance. Limited experimental tool wear studies have been carried out and tool life predictions are performed for dry machining using an established analytical tool wear model. Finally, a suitable tool material, out of three selected ones, for the specific grade of WHA is recommended.

2. MATERIALS AND METHOD

2.1 Experimental Details

The performances of commercially available DNMG150608 cemented carbide inserts of uncoated, CVD coated (TiN-TiCN-Al_2O_3-ZrCN), and PVD (AlTiN) coated grades (Make: Widia) were evaluated and compared during turning WHA. Coating thickness and distribution of layer materials were identified by studying the fractured cross-sections of inserts as illustrated in Fig. 1(a). Micro geometry such as edge radius, chip breaker were varying as the grades were chosen based on best practice. The inserts were mounted on tool holder type DDJNL2020K15 (Make: Widia) which offered -5^0 rake angle, 93^0 major cutting edge angle and 32^0 end cutting edge angle. The elemental composition and properties of the alloy as well as the specification of the inserts are presented in Table 1.

2.1.1 Tribological studies

The wear tests were conducted under dry conditions using Pin-on-disc setup (Make: MAGNUM). The pins of 4 mm diameter were cut from the selected cutting tool inserts using wire cut EDM, while the disc of 32 mm diameter was prepared from WHA. Both were mounted with the help of adapters. It is to be noted that Electric discharge machining was done using lower values of peak current and pulse duration so that the depth of damaged layer of tungsten carbide is lower.[14] The pin on disc tests were conducted at a sliding velocity of 30 m/min and a normal load of 40 N. These parameters were chosen to emulate conditions existing in machining. A track diameter of 24 mm was chosen for a track length of 750 m. Weights of pins were measured before and after tests using a precision balance (Make: Shimadzu) to calculate specific wear rate. The pin surfaces before and after tests were examined using SEM-EDX technique. The experimental set up to study the tribological properties are shown in Fig. 1(b)

Table 1. Specifications of 85 WNCF alloy and cutting tool inserts

	Workpiece	Insert Grade		
Grade/ Composition	W85-Ni8-Co4-Fe3	Uncoated	CVD TiN-TiCN-Al_2O_3-ZrCN	PVD AlTiN
Density (g/cc)	16.4	14.40	14.30	14.50
Hardness (HV)	586/419 (Grain/Matrix)			
Flank face roughness (µm)	_	0.598	0.699	0.370
Coating thickness (µm)	-	-	8	2

2.1.2 Machinability Tests

The turning tests were conducted on CNC lathe (Make: HMT PTC200). The workpiece material, 85WNCF grade WHA with dimensions of 25 mm diameter and 110 mm length, was turned under wet and dry cutting conditions at cutting speed of 30 m/min and depth of cut of 0.6 mm with varying feed rates (0.05, 0.15 and 0.20 mm/rev). For wet machining, water emulsion lubricant was used at a discharge rate of 12 L/min. Under dry conditions cutting forces were measured using 3 axis piezo electric lathe tool dynamometer (Make: NK Instruments) and thermal imaging camera (Make: FLIR E60) was used to measure cutting zone temperature. The machining forces and temperature were not measured under wet conditions considering the ingress protection capabilities of the instruments used. In each instance, a portable surface roughness tester, Mitutoyo SJ-410 was used to measure surface roughness. Chips were collected during machining to study chip morphology under optical microscope (Make: Olympus) as well FE-SEM (Make: FEI). Machined surfaces were observed under FE-SEM for surface damage examination. Tool wear tests were conducted on both grades of coated inserts keeping the cutting speed at 30 m/min, depth of cut 0.6 mm and feed at 0.2 mm/rev under wet cutting conditions. Flank face was examined under SEM to study the flank wear. The experiment set up for conducting machining tests and cutting conditions are shown in Fig. 1(c).

2.2 Analytical Model for Tool Wear

The tool wear rate can be defined as a function of machining variables using analytical tool wear models in terms of volume loss of tool face per unit contact area per unit time. Sagar, *et al.*[6] proposed a new model based on adhesion wear mechanism observed in machining of WHA. The proposed modified form of Zhao model found to be a robust model fitting well over wide range of rake angles and temperature varying non linearly during machining. Since this model has proven its applicability in WHA machining and solely depends on the cutting forces and temperature developed during machining, it

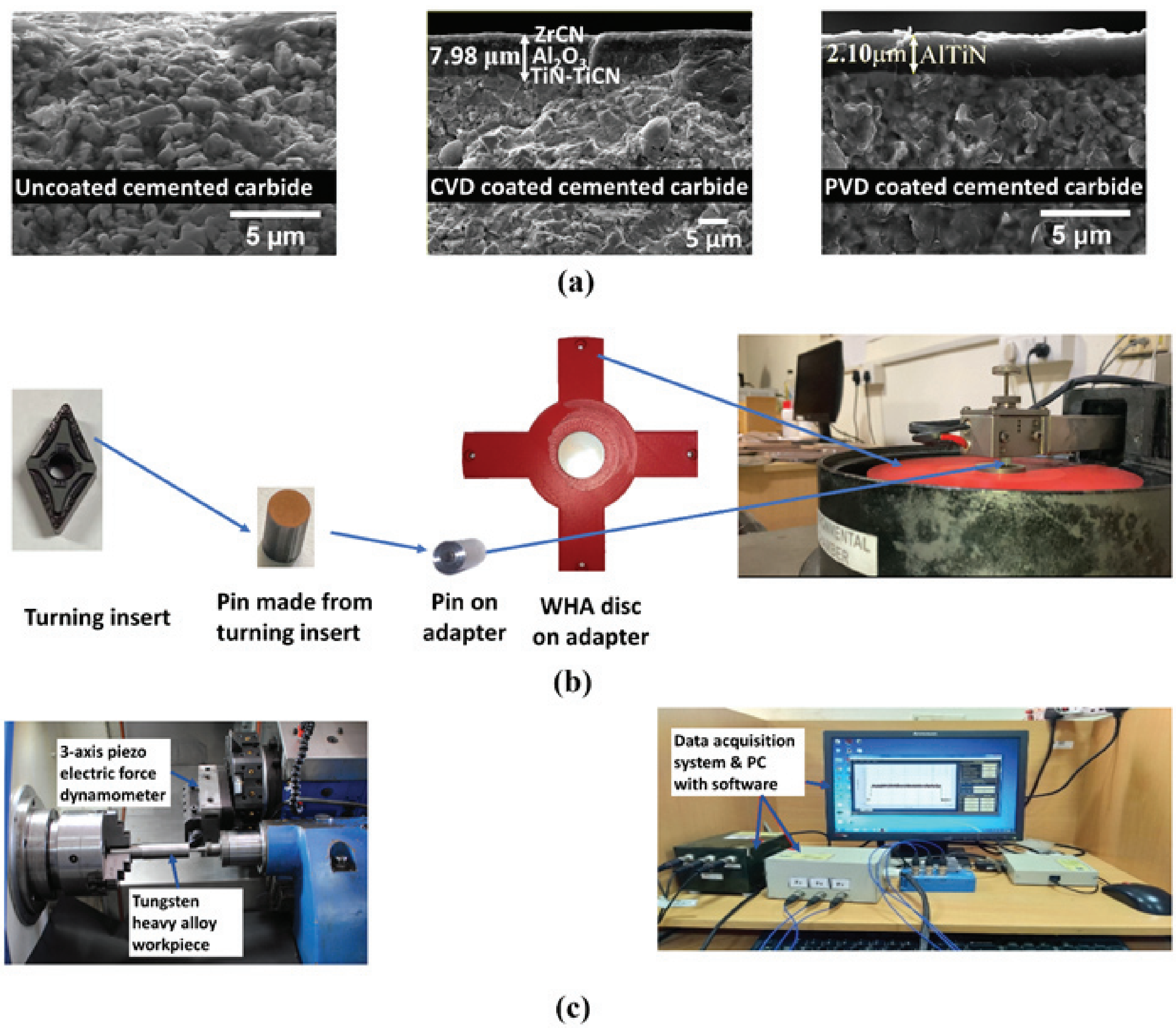

Figure 1. (a) Fractured cross-sections of inserts, (b) Tribological characterisation set up, and (c) Experimental setup for machining experiments.

was considered to predict the tool lives of three different types of inserts used in present study. In this model, the wear land measurement V_B in µm can be expressed as

$$V_B = D\left(\frac{2(\cot\alpha - \tan\gamma)v_c}{a_w^{\,2}}\right)^{\frac{1}{3}}\left(\frac{F_t t}{Z}\right)^{\frac{1}{3}} \quad (1)$$

where, D is a coefficient based on tool wear experiments. F_t, time-dependent thrust force in N for -5^0 rake angle and Z, temperature dependent tool hardness calculated using Equations (2) and (3).

$$F_t = F_{ti} \times t^{0.0556} \quad (2)$$

The temperature dependent tool hardness varies according to the tools used. The hot hardness for uncoated cemented carbide insert can be calculated as explained by Sagar, *et al.*[6] as the grade of inserts are same in both cases. For the multilayered CVD coated tool, the hardness values of different layers were averaged[15] to correlate it with the cutting temperature and for PVD AlTiN coated insert, it was obtained based on the behaviour of an equivalent coating.[16]

$Z = 6*10^{-6}\theta_f^3 - 5.4*10^{-3}\theta_f^2 + 0.5853*\theta_f + 1517$, for uncoated cemented carbide

$Z = 2412.35*e^{\left(-1.304*10^{-3}\theta_f\right)}$, for CVD multilayered coated carbide

$Z = -1.4*10^{-3}\theta_f^2 - 0.27450\theta_f + 2557.8$, for PVD AlTiN coated carbide (3)

Cutting temperature θ_f for -5^0 rake angle was given as:

$$\theta_f = 3.5*10^{-6}t^2 + 4.1*10^{-2}t + \theta_{fi} + \Delta\theta_{At} \quad (4)$$

$\Delta\theta_{At}$, the average temperature rise as a function of heat generated and cutting length, was considered as;

$$\Delta\theta_{At} = \frac{2Ql_c}{k_w\sqrt{\pi(1.27S_{ei} + P_{ei})}} \quad (5)$$

Tool flank-workpiece contact length, l_c, was calculated as per Eqn. (6) . S_{ei} the endurance limit of the material equaled to 425 MPa[17] and P_{ei}, Peclet number was determined by Eqn (7).

$$l_c = 2f(\zeta(1-\tan\gamma) + \sec\gamma) \quad (6)$$

$$P_{ei} = \frac{v_c a_w \rho c_p}{k_w} \quad (7)$$

The tool life was predicted as the cutting time in minutes to reach a maximum flank wear of 600 µm as per ISO 3685 standard.

3. RESULTS AND DISCUSSION

3.1 Tribological Characterisation

Since the machinability characteristics depend on tribological phenomena,[10] the pin on disc tests could be used to get a better insight into the interaction between the machined material and tool material. The specific wear rate and the coefficient of friction are measured for the given cutting tool inserts. The variation in coefficient of friction against sliding length is illustrated in Fig. 2(a). The uncoated carbide pin, CVD coated pin and PVD coated pin are observed to have closer average friction coefficient with values of 0.51, 0.54 and 0.49 respectively. However, the trend of the same appeared to vary with increasing sliding length. The uncoated pin has shown a largely stable coefficient of friction values throughout out the test, reducing slightly after 500 m of track length. It is observed that the wear debris formed during the test are adhered to the contact surface of pin to form a layer which could have reduced

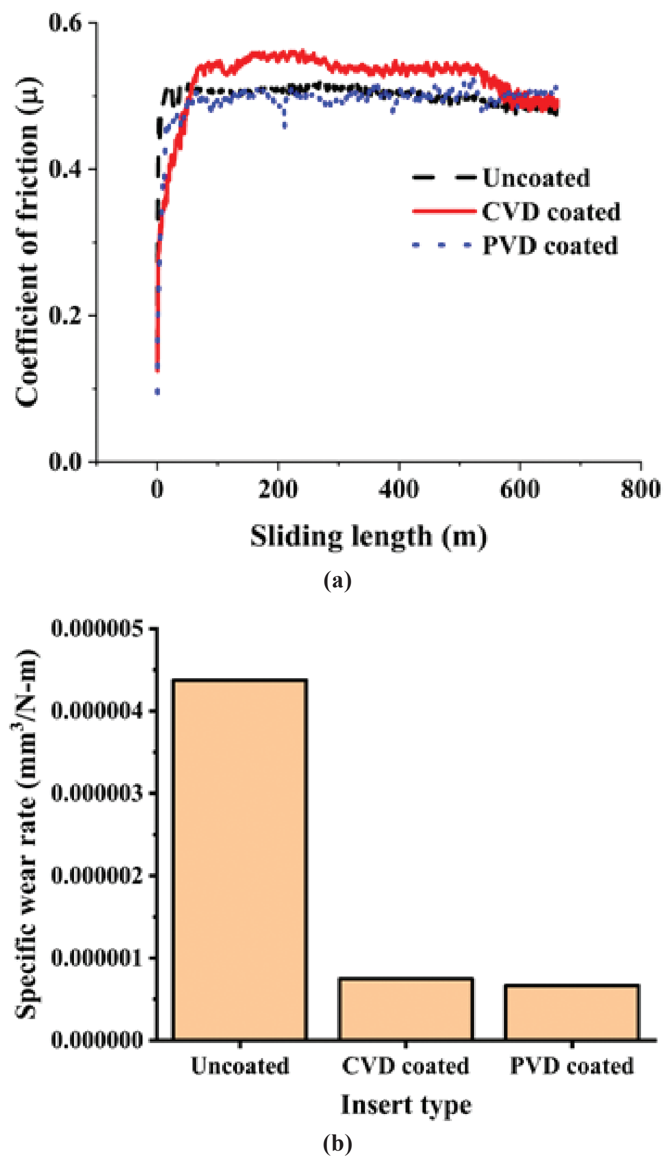

Figure 2. (a) Coefficient of friction vs Sliding length, and (b) Variation of specific wear rate with coating type.

the friction coefficient. The CVD coated pins have initially shown a larger coefficient of friction which reached up to 0.58 and later reduced to values closer to uncoated pins. The higher surface roughness on the insert flank face as depicted in Table 1 could be a reason for the higher friction coefficient despite it being a coated surface. Specific wear rate has been calculated using Eqn (8) and presented in Fig. 2(b).

$$Wsp = \frac{\Delta W}{\rho_p FL} \tag{8}$$

The uncoated pin has shown the largest wear rate approximating to 6 times that of CVD coated pin and 6.6 times that of PVD coated pin while PVD coated pin exhibits lowest wear rate.

The surface and EDS analysis of the pins before and after the wear test are shown in Fig. 3. The post-test EDS analysis of surfaces reveals a higher amount of WHA adhesion on uncoated surface followed by CVD TiN-TiCN-Al_2O_3-ZrCN coated surface and the least on PVD AlTiN coating. The adhesion is higher in the regions where the coating has peeled off, exposing the tungsten carbide substrate. The formation of highly stable Al_2O_3 nano tribo-films from AlTiN coating reduces the friction as well as reduces the workpiece adherence on the coated surface.[18] On the other hand, top ZrCN layer on CVD coated tools tend to produce ZrO_2 layer on the surface which has a higher frictional coefficient than Al_2O_3 against the elements constituting the WHA.[19–21]

3.2 Machinability Tests

3.2.1 Cutting Forces, Temperature, and Surface Roughness

Machinability is assessed by measuring the cutting forces, temperature and surface roughness, the variation of which as a function of feed is presented in Fig. 4. From the graphs presented in Fig. 4(a), it is quite evident that both the forces and temperature increase with feed rate. The length of contact increases with feed rate, as per Eqn (6) , which resulted in larger contact area and thus, higher forces and temperature. The CVD coated inserts have shown the highest cutting forces with values ranging from 15-20 % higher than PVD coated inserts. Uncoated inserts have shown lower cutting forces at lower feed rates which increased rapidly at higher feed rate. The increased Built-Up Edge (BUE) formation and larger tool wear rate could be the reason. The trend remained the same for measured chip temperature values also. Though coated inserts were expected to produce better results for cutting forces and temperature, the CVD coated inserts could not outperform the uncoated inserts under the specified cutting conditions, especially at lower values of feed. At lower cutting speeds, effect of formation of BUEs due to increased affinity of coating material to the workpiece material as found during the pin-on-disc experiments could possibly be the reason for this observation. It has been reported that higher coating thickness leads to larger tool edge radius which causes larger cutting forces and ploughing force components and higher temperature.[22]

From pin-on-disc tests it is observed that the ZrCN layer of CVD coated tools offered higher friction with WHA disc, followed by uncoated insert and AlTiN layer of PVD coated tools. At lower cutting speeds the effect of friction being higher would have resulted in higher cutting forces and temperature which matched with that of the experimental observations. The formation of tribo-films during friction[18] which provides enhanced frictional conditions and increased hot hardness while machining with AlTiN coated inserts could be a possible explanation for the better performance of PVD coated tool over the CVD coated and uncoated tools.

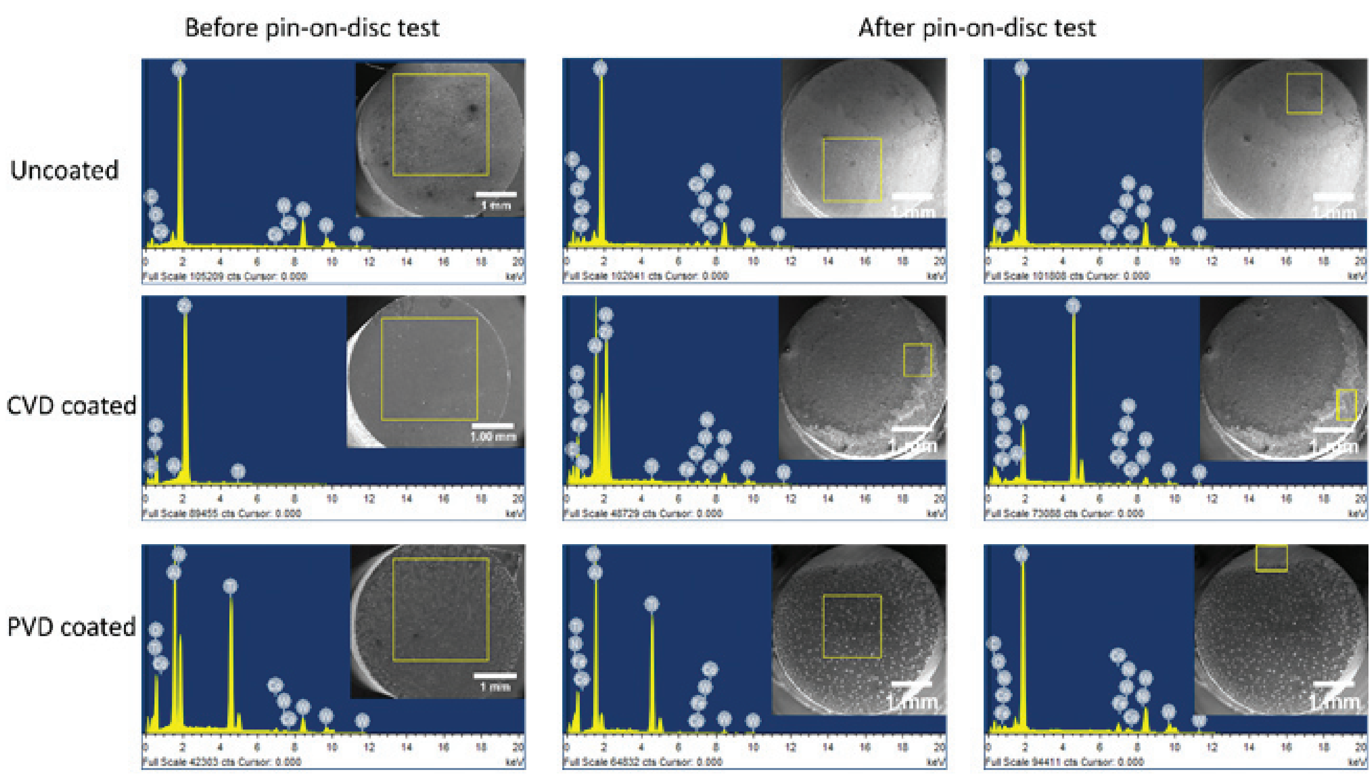

Figure 3. SEM EDS analysis of uncoated, PVD coated and CVD coated pins.

Figure 4(b) shows the variation of surface roughness with variable feeds using uncoated and coated inserts. Arithmetic mean surface roughness value (R_a) is considered. As expected, surface roughness increased with feed and decreased under wet cutting conditions. While the increased thrust force at higher feed rates increases the surface roughness, the lower amount of chatter at lower feed rates enhances the finish.[23] Friction at chip-tool interface, BUE formation and tool wear govern the surface roughness. Inserts with PVD coating of AlTiN have outperformed both the other inserts under explored conditions. The uncoated inserts have provided the least surface finish among the three with roughness values 40-60 % greater under dry conditions and 90-400 % greater under wet conditions than the PVD coated inserts. The thin coating and ability to keep sharper cutting edge of PVD coated tool might have resulted in its better performance. Also, it may be noted that PVD coated pins exhibited least coefficient of friction during pin-on-disc tests. On the other hand, the higher wear rate and increased affinity of tool material towards the machined material, as evident from pin-on-disc tests, would have resulted in higher amount of BUE formation, thus leading to degraded surface quality with uncoated inserts even if they displayed lesser coefficient of friction than CVD coated inserts, during pin on disc tests. The SEM images of the resulting surface conditions after wet machining with uncoated, CVD coated and PVD coated inserts at 0.2 mm/rev are illustrated in Fig. 4c. Clearly, PVD coated inserts produced a surface with least defects while surfaces produced with uncoated inserts have shown tearing and smearing. Presence of adhered material has drastically reduced the surface quality.

3.2.2 Chip morphology

It is observed that morphology of the chip varied with the type cutting tool used. Both uncoated and CVD coated tools tend to produce fragmented chips while PVD coated tools produce relatively longer and even continuous chips. Consequently, the back surface and free surface of the obtained chips under varied conditions are studied from the SEM images, as shown in Fig. 5. The free surfaces have shown a rough, lamellar pattern, while back surfaces appear smoother. Smoother chip back surface implies most favourable conditions of friction existing at the interface of chip and tool. Among the three, PVD AlTiN coated inserts produce chips with smoothest back surface, followed by CVD coated inserts. Such a trend could be directly correlated to the surface finish produced. The smoother chip surfaces are observed with coolant for all three inserts indicating improvement in surface finish. The lamellae observed on the free surface appear to be

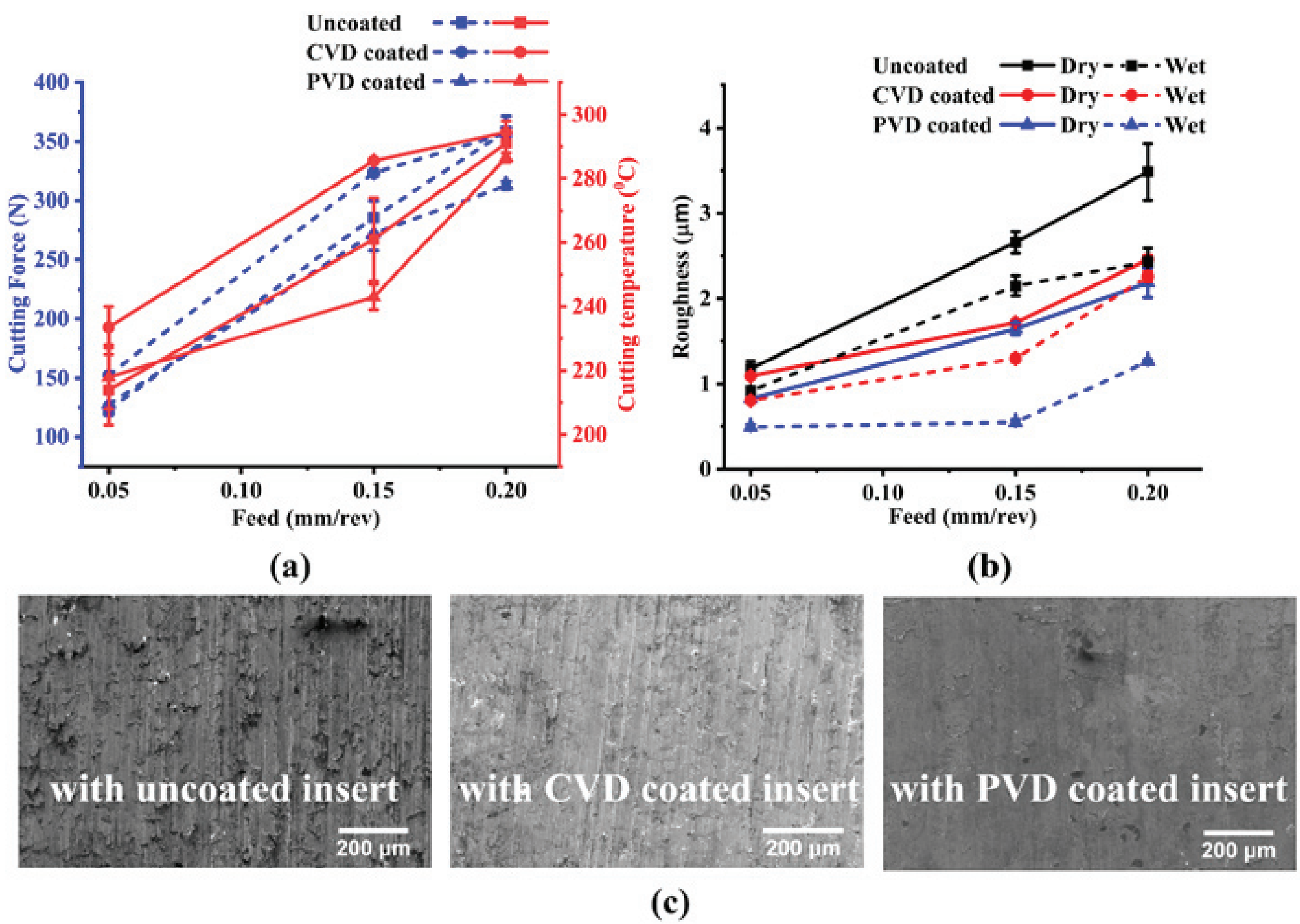

Figure 4. (a) Cutting force and cutting temperature vs feed under dry cutting conditions, (b) Surface roughness vs feed under dry and wet cutting conditions, and (c) machined surfaces at feed = 0.20 mm/rev under wet condition.

more uniform and smaller for PVD coated inserts. It appears to be more non uniform and deeper for other inserts and at lower feed rate hinting towards increase in chip segmentation. The chip thickness varies along the cutting edge, being minimum towards the trailing edge. The edge serration is prominent at the trailing edge of chip for lower feed rates and dry condition for uncoated and CVD coated tools.

3.2.3 Tool Wear Measurements and Tool Life Predictions

A basic level tool wear study is conducted on both CVD and PVD coated inserts keeping the depth of cut 0.6 mm, feed at 0.2 mm/rev and cutting speed at 30 m/min under wet cutting conditions. Fig. 6 shows the SEM images of the flank surfaces of the worn-out inserts after 160 seconds of machining. It can be observed that the PVD coated insert has shown lower values of flank wear with no prominent edge chipping in the initial stages of tool wear. Furthermore, BUE is also observed in case of CVD coated inserts. Such phenomena could be correlated to the type of wear mechanism observed during the pin-on-disc test where an adhesive wear mechanism was evident for the CVD coated inserts. Also, increased tendency to form BUE could be a reason for lower surface finish and higher forces even though CVD coated tools exhibited a slightly lower coefficient of friction as compared to that of PVD ones. Any

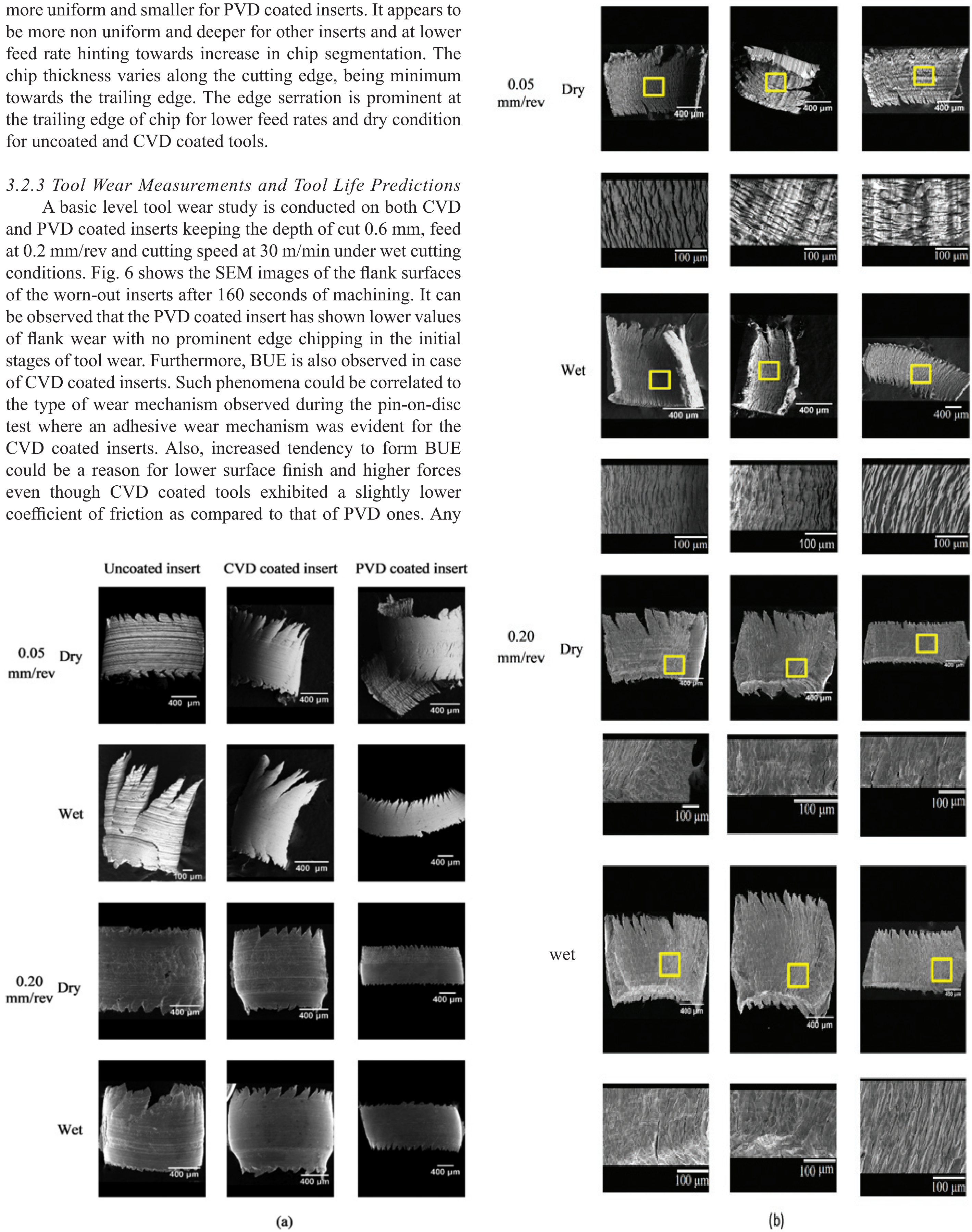

Figure 5. SEM images of: (a) Chip back surface, and (b) Chip free surface for the selected cutting tools.

sort of embrittlement within the coating which CVD coatings tend to have, affects its performance in machining materials with inconsistent microstructure. Titanium aluminium nitride coatings with their enhanced ductility are suitable for such interruptions in cut.[24-25] Thus the microstructure of WHA with spherical tungsten grains suspended in a Ni-Co-Fe matrix can also influence the observed difference in the performance of different types of inserts.

The modified Zhao model is used for predicting tool life at varied cutting conditions by considering maximum flank wear achieved to be equal to 600 µm as the failure criterion. Fig. 6(c) presents the tool life values at different feed rates under dry conditions. The selected tool wear rate model could capture the decreasing trend of the tool life, which is expected, with the increase in feed rate satisfactorily. It can be seen that PVD coated insert performed fairly well compared to uncoated and CVD coated inserts.

Overall, it can be observed that PVD coated inserts have proven effective for machining WHA under the given cutting condition where a lower value of cutting speed and relatively higher value of depth of cut were considered. The formation of BUE is very much expected under the selected cutting parameters. From the pin on disc tests, it is clear that adhesion is more prominent for uncoated and CVD coated inserts. AlTiN coating can reduce the tool-chip interface adhesion bond strength and severity of the friction.[24] Adhesion being one of the major factor for the development of BUE during machining, both uncoated inserts and CVD multilayer coated inserts have shown higher tendency of forming BUE during machining tests as compared to that of PVD coated inserts. Consequently, cutting forces and surface roughness values also are higher for uncoated and CVD coated inserts. The chip morphology results also came in line with the machined surface conditions. However, for rough turning WHAs uncoated and CVD coated inserts can be used satisfactorily by considering relatively higher cutting speeds. But if the surface finish is the major concern, PVD coated inserts will always be a better choice.

4. CONCLUSIONS

- A detailed comparison of the performance of three different cutting inserts has been carried out while machining 85WHA.
- The pin on disc tests have been conducted for the said

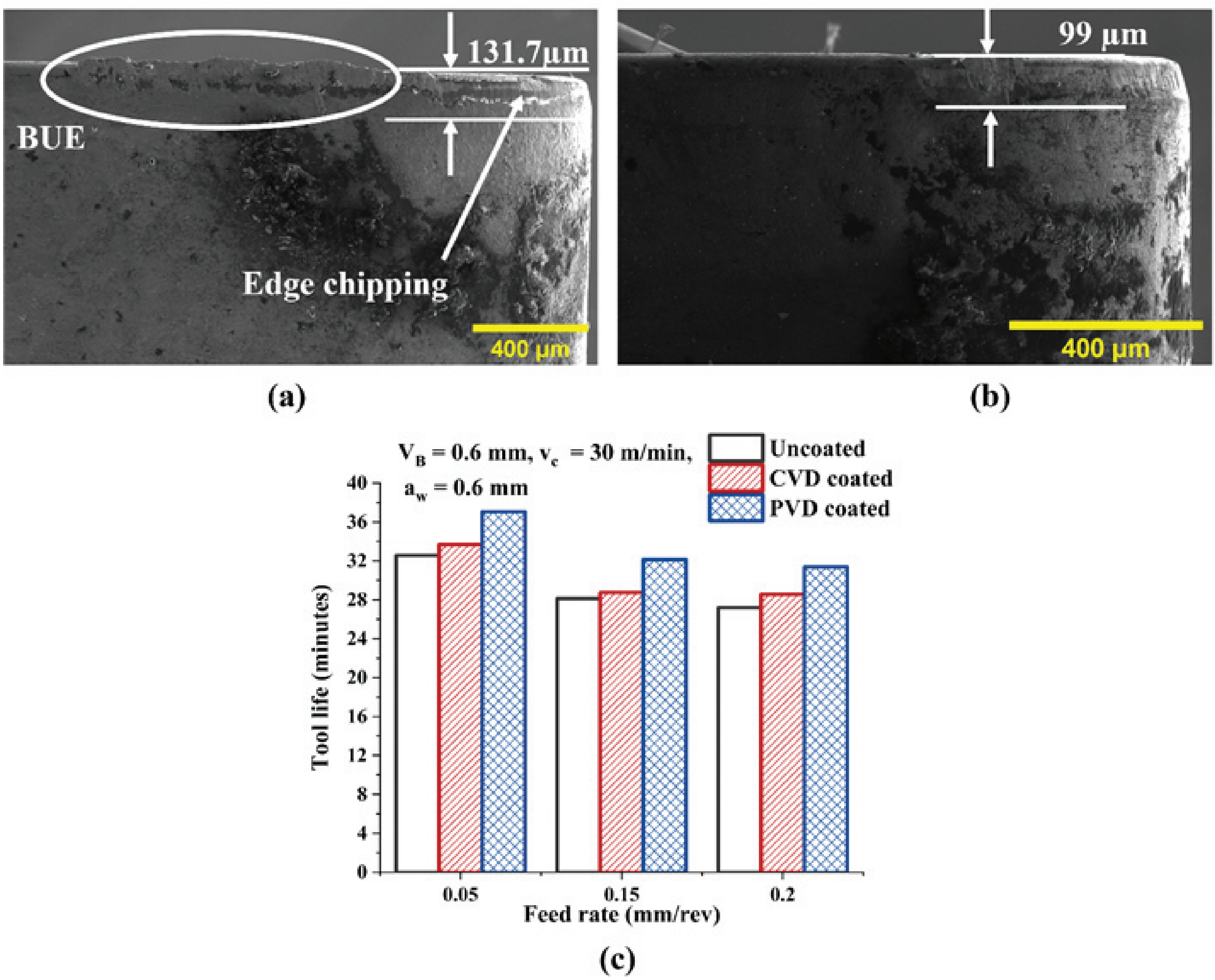

Figure 6. SEM images of tool wear after 160 seconds for: (a) CVD coated, (b) PVD coated inserts, and (c) Tool life at different feed rates as per modified Zhao model.

cutting inserts by taking 85WHA as the counterpart to understand the tribological properties and the wear mechanism. The results indicated that AlTiN coating on the PVD coated insert has lower affinity towards WHA in order to form BUEs and lower wear under sliding friction.

- Machining tests have been conducted under varied conditions and it is observed that PVD AlTiN coated inserts provide the best surface finish as well as lowest values of cutting forces and cutting temperature. The chip morphology, surface quality and finish indicate better performance of AlTiN coated inserts for wet machining too.
- Basic tool wear studies showed that edge chipping is more prominent in case of CVD coated insert. The irregularity in the microstructure of WHA with harder tungsten grains intermittently appearing in relatively softer matrix might be a reason for chipping of thicker CVD coatings.
- Modifed Zhao model has been successfully used for the tool life predictions under the given cutting conditions. PVD coated inserts show relatively longer tool life as compared to uncoated inserts and CVD coated inserts.
- Overall, PVD AlTiN coated inserts prove to be promising candidates for the given cutting conditions.

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