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Study on wear morphology of uncoated and MT-CVD TiCN-Al_2O_3 Coated Carbide Inserts during dry machining of Inconel 825 superalloy

Gobinda Chandra Behera[a], Sarthak Prasad Sahoo[a], Soni Kumari[b], Saurav Datta[a]1

[a]Department of Mechanical Engineering, National Institute of Technology, Rourkela-769008, Odisha, India
[b]*Department of Mechanical Engineering, GLA University, Mathura, Uttar Pradesh 281406, India*

Abstract

The adoption of the *High Speed Machining* (HSM) approach by industries to enhance productivity is crucial in order to fulfill the growing demand of the global market. Understanding superalloys' machining behavior is also necessary since they play a significant role in a variety of industries, including the aerospace industry, marine engine parts, biomedical applications, chemical and petrochemical industries, and nuclear fuel processing plants. Hence, dry machining performance of '*difficult-to-cut*' aerospace superalloy Inconel 825 is studied herein. With uncoated and MT-CVD TiCN-Al_2O_3 coated carbide inserts, machining experiments are performed at various cutting speeds. Detailed tool wear mechanisms are discussed for each of the cutting inserts with regard to different cutting speeds and hence the performance gain with coated carbide tools is understood as compared to its uncoated counterpart for dry machining of Inconel 825 superalloy.

Keywords: Dry machining; superalloy; Inconel 825; flank wear; tool wear

1. Research background

Among the variety of high-temperature alloys (i.e. superalloys), nickel-based alloys (Inconel) gain much concertation nowadays due to their extensive usage in aerospace components, and modern jet engine parts [1]. Inconel 825 is a nickel-based superalloy that exhibits excellent mechanical strength, strong oxidation and corrosion resistance, thermal stability, and creep resistance at elevated temperatures. Superalloys are also called 'difficult-to-cut' due to tendency of rapid work-hardening; superalloys possess poor thermal conductivity, high affinity to react, and high-temperature strength. During machining, selection of suitable tool materials, and exploration of different coatings, onto the cutting tools are trending areas for researchers as the lubricants (meant for reducing cutting heat) often lead to operators' health issues and adverse environmental effects. Also, the elevated production cost (for purchase and disposal of the lubricants) can be minimized in case of dry machining or near dry machining i.e. Minimum Quantity Lubrication (MQL) [2]. Traditional dry machining is indeed challenging but it may perform efficiently with HSM upon selecting proper tool inserts (cemented carbide, cermet, SiAlON, CBN) as well as appropriate coating(s) over tool substrate.

Major problems during machining of Inconel were experienced as lower tool life and inferior integrity of the machined work surface. During HSM of Inconel 718, Bhatt et al. [3] suggested that uncoated WC-Co is the most preferred cutting tool for low cutting speed whilst improvements can be witnessed with coated carbide tools. This study revealed coating layers (CVD-TiCN/Al_2O_3/TiN) performed better due to their high wear resistance, whereas PVD-TiAlN coating exhibited satisfactory performance as compared to uncoated tools. TiCN and TiAlN coated tools exhibited better results for Inconel 718 machining than a TiN coated tool, during dry cutting conditions. Compared to TiAlN, TiCN and TiN coated tools experienced notch wear, and crater wear which contributed to improved tool life [4]. Enhanced tool life with fine-grained morphology was experienced with coated carbide tool (coated with PVD TiAlN and AlTiN, AlTiN layers) during dry turning of Inconel 718. Formation of built-up edges

* Corresponding author. Tel.: +91 661 246 2524.
E-mail address: sdatta@nitrkl.ac.in

(BUEs), adhesion, and welding of work-alloy materials on flank and rake faces were found to be dominant wear modes [5]. Among a variety of PVD-coated tools separately coated with: CrN+CrN: C+C, TiN+AlTiN, and TiN+AlTiN+MoS_2 coatings, the TiN+AlTiN+MoS_2-coated tool was reported to be satisfactory for Inconel 718 machining under dry and MQL environments [6]. With increased cutting speed, reduced force components and thinner chips were observed for Inconel 718 machining, due to reduced contact area and partly drop in shear strength. With intense heat generation at tool-chip interface, the cutting tool greatly suffered through abrasive wear [7, 8]. For Inconel 718 machining, formation of cracks at substrate-coating interface, edge chipping and adhesion wear at low cutting speed and oxide layer formation at tool-chip interface at medium cutting speed were observed for PVD-coated carbide tool. At high cutting speed, such oxide layer was broken and caused formation of wear debris [9]. Application of some of the harder tool materials (like ceramics, CBN and PCBN) and their wear modes during machinability investigation of different Ni-based alloys were also reported previously [10-12]. However, high tool purchase costs could also result in higher cost of production, which would be undesirable from the perspective of the industrial economy.

With adhesion, diffusion, plastic deformation, and catastrophic failure of uncoated tools, CVD multi-layered coated (with TiN/TiCN/Al_2O_3/ZrCN coating) tools with improved wear resistance were found to perform better for dry turning of Inconel 825 [13]. In relation to dry turning of Inconel 825 with PVD-TiAlN/TiN coated inserts, CVD-TiCN/Al_2O_3 coated inserts, and uncoated carbide tool inserts; uniform chip morphology was ascertained for coated tools than an uncoated tool. Uncoated inserts were greatly suffered by adhesion, cutting edge chipping, and notching; occurrence of which could be minimized by the application of PVD coated tools [14]. When material was removed from Inconel 825 alloy under dry conditions using a PVD-AlTiN coated carbide tool, it was discovered that surface roughness and cutting forces rose with an increase in feed rate and doc, and dropped with an increase in cutting speed (at constant feed and doc) [15].

From the literature survey, it is realized that a substantial volume of research was conducted on machinability of nickel based superalloys (especially, Inconel 718) in purview of tool wear, tool life, and chip morphology. However, literature is sparse on examining machinability characteristics of Inconel 825 superalloy. To this end, present study focuses on dry machining response of Inconel 825 in consideration with uncoated, and CVD (TiCN-Al_2O_3) bilayer coated carbide tool inserts. The productivity of machining is assessed through quantitative and qualitative evaluations of tool wear.

2. Material and methods

The workpiece, considered for the present machining experiments, is an Inconel 825 superalloy round solid bar with an initial diameter of 58.8 mm. All the machining trials are carried out on a heavy-duty high speed precision lathe (NH 26, HMT, Bangalore, India) without employing any cutting fluid i.e. under dry cutting conditions (Fig. 1a). The experimental setup is furnished in Fig. 1a, which shows the tool-post is fitted with a PSBNR2020K12-type tool holder (WIDIA, India) to provide standard ORS signature of -6°, -6°, 6°, 6°, 15°, and 75°. For the present experimental evaluation, two inserts from Kennametal (India) are used: a TTS-P25 graded uncoated carbide insert (SNMG120408) and a KCM15B graded coated carbide insert with MT-CVD TiCN-Al_2O_3 coating (SNMG120408MP). The chosen cutting tools have same carbide substrate and same tool signature, except upper coating layers (in the latter one). Also, post-heat treatment over the coated insert improves coating adhesion, truncates tendency towards micro-chipping, and edge build-up, and favorably influences workpiece surface finishes; which are expected to be beneficial for machining as compared to the uncoated carbide insert.

As tungsten carbide (WC) is the most popular tool material specially used for HSM, microstructure of uncoated WC-Co insert, commonly produced through powder metallurgy, is shown in Fig. 1b. From this figure, hard refractory carbides (hexagonal WC phase), mixed cubic carbides/ carbonitrides of the transition metals (Group IV, V, VI of periodic table), also called γ-phase (or fcc-phase) embedded in a soft (ductile) Co binder matrix can be seen for the used uncoated tool. The irregularly distributed grey-colored phase is γ-phase; WC grains are viewed as white in color. The black area locating WC/WC and WC/γ-phase boundaries indicates presence of Co binder [16]. Details of substrate and coating layers of the bi-layered coated tool obtained through optical as well as scanning electron microscopy are presented in Fig. 2.

The bi-layer coated tool with WC substrate, used in the present work, is composed of, an inner TiCN layer adhering to the carbide substrate and an outer alumina coating layer (Fig. 2a). Alumina coating is uniquely used due to its chemical inertness and high hot hardness [17], while some notable mechanical properties of TiCN can be listed as: hardness: 87 Rc; oxidation temperature: 400 ºC; friction coefficient: 0.45. The inner layer imparts strength to the cutting edge by improving toughness and restricting tool flank wear, whereas topmost Al_2O_3 layer with lower thermal conductivity acts as a thermal barrier, which made the tool suitable for applications at higher cutting speeds. In case of turning, higher temperatures are generated at tool-work interfaces; but lower thermal conductivity of Al_2O_3 coating layer restricts evolved heat to be transferred through tool substrate. Hence, maximum amount of generated heat is carried away by flowing chips. Thus, this property is likely to enhance tool performance. Thickness of the coatings is measured from Fig. 2b, which is measured by using *ImageJ* software; the average values are: Al_2O_3: 7.4 µm, and TiCN: 10.8 µm.

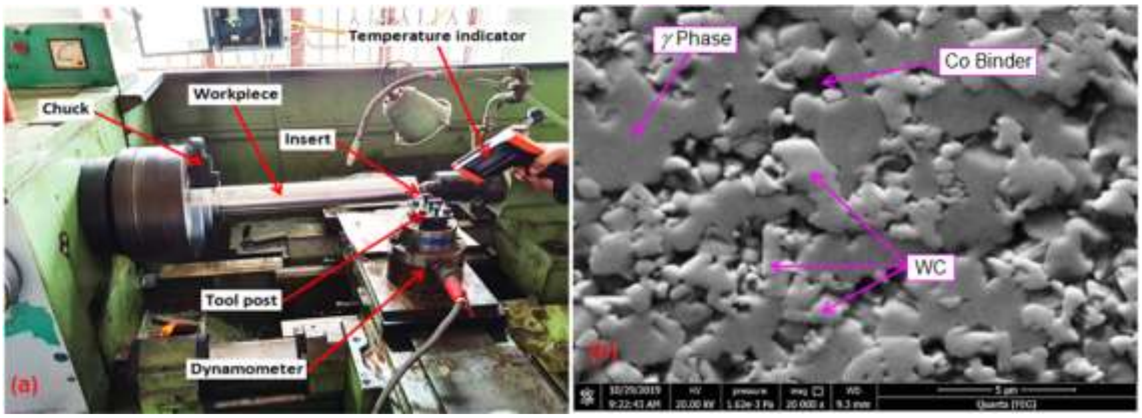


Fig. 1. (a) Experimental setup, (b) Microstructure of uncoated WC-Co tool substrate.

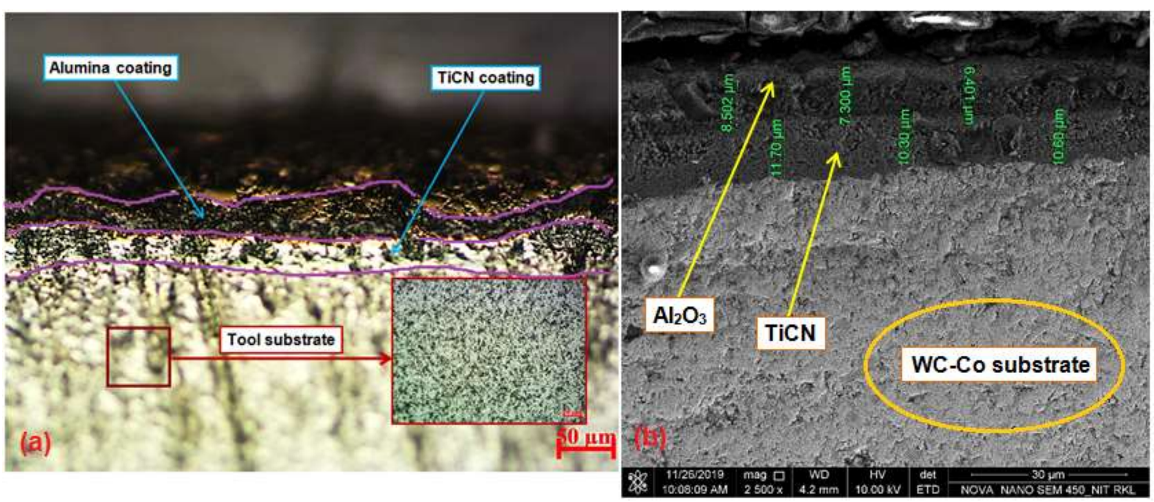


Fig. 2. Microstructure of coated tool as observed through (a) Optical microscopy, and (b) Scanning electron microscopy.

At four separate machining speeds (50 m/min, 65 m/min, 85 m/min and 112 m/min), dry turning experiments are performed at constant tool feed (f = 0.1 mm/rev) and constant depth of cut (doc = 0.25 mm). With multiple trials (each trial of 40 s) under one set, four different sets of experiment are carried out for each insert type. To investigate the wear modes completely a fresh cutting edge of the insert is employed for each turning set. Equipment facilities like optical microscopy and scanning electron microscopy with Energy Dispersive X-ray Spectroscopy (EDS) are availed for in detail analysis.

3. Results and discussion

As wear of a tuning insert is commonly presented through rake face wear (crater wear) and flank face wear (flank wear), hence these two surfaces are to be analyzed in detail to understand the complete wear process during a metal cutting operation. It is also said that when cutting speed increases, tool wear quickens as a result of an increase in temperature at the cutting edge and thus the plastically deformed cutting edge loses its strength to perform further machining operations [7, 8]. Though tool flank wear depends on tool geometry, cutting condition, and hardness of workpiece as well as tool insert, it does not accurately reflect the wear processes that the cutting inserts go through. Hence, the complete wear modes of the employed cutting inserts are studied through scanning electron micrographs.

Fig. 3 exhibits wear modes of uncoated carbide insert at 65 m/min. With noticeable flank wear, tool rake face is found to be unaffected except some broken chip fragments. The wear modes that are most obvious on the tool surfaces include abrasion, adhesion, and tool attrition. The presence of hard particles or hard inclusions with sharp edges in work material (examples are: carbides, oxides, nitrides, and other nonmetallic inclusions), that come into contact with the tool surface is what causes abrasion. Progression of machining leads to intense heat generation at tool-chip interface; high temperature chips, thus, get softer and behave ductile in nature. Often, these ductile chips stick on tool faces (chip sticking) as reported by Goindi and Sarkar [2]. On the tool surface, material adhesion takes place as a result of high temperature and pressure at the cutting zone. Presence of majority of work-alloy elements (Ni, Cr, Fe, Mo, Ti, etc.) in the selected sections (as shown in Fig. 3) however confirms material adhesion on the tool surface. The sliding of the chips sometimes gets affected by unstable material adhesion; for which some of the tool materials are also carried away, as partial detachment happens at the adhesive sections. Thus the tool substrate is exposed forming attrition wear as explained by Antonialli et al. [18]. EDS spectra (in Fig. 3), at the attrition zone, also detected enough amount of tool constituent elements like W, C, Ti, and Co along with a negligible amount of residues of some work material (Mo and Cr). Inadequate compaction of tool material may also accelerate attrition wear. Attrition affected tool face creates sites for further adhesion.

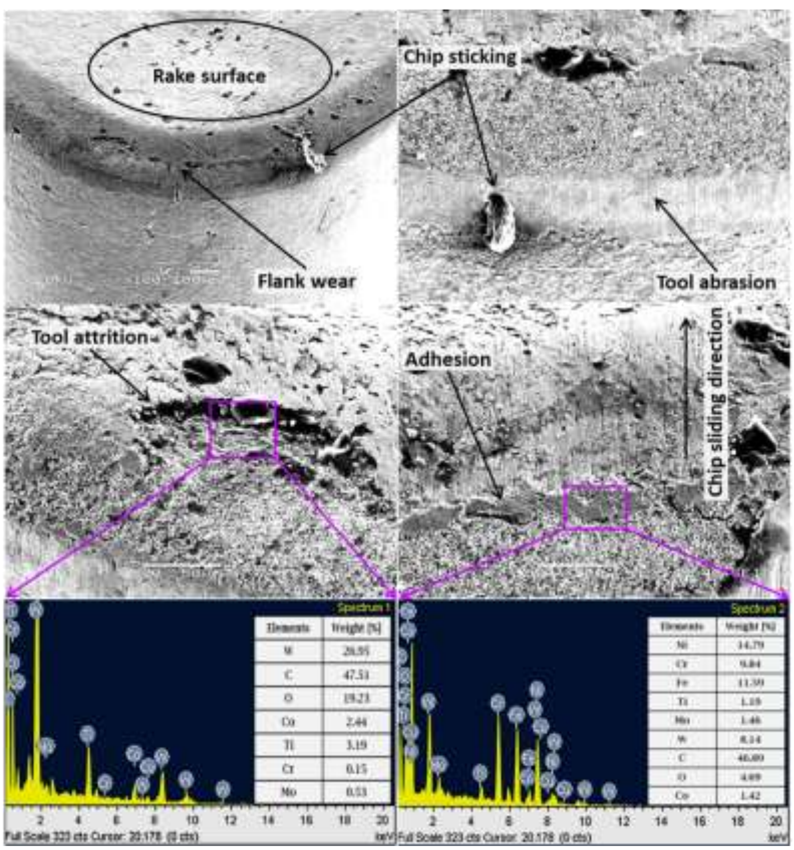


Fig. 3. Wear mechanisms as observed in worn-out uncoated insert (V = 65 m/min).

Similar to Fig. 3, identical wear modes are also noticed for uncoated tool at highest cutting speed (~ 112 m/min) and are presented in Fig. 4. Oxidation and fusion of chips are clearly marked herein as are tool attrition, abrasion, and adhesion of work material. At the cutting speed of 112 m/min, huge cutting pressure and temperatures are produced at the cutting zone because of the extreme interfacial frictions. Produced hot chips when exposed to atmospheric air, get automatically oxidized which is indicated as chip oxidation (in Fig. 4). These oxidized chips are prone to settle or fused at rake face of cutting tool in the vicinity of cutting edge (fusion of oxidized chips) due to generation of high pressure and temperature. A similar observation was also reported by Thakur and Gangopadhyay [14]. Presence of 71.50 % (by weight) of carbon and 15.60 % (by weight) of oxygen at the oxidation zone supports the above stated process to be true. The flank face is seen to be affected mainly by adhesion and abrasion; out of which amount of adhesion herein is found to be greater than that of in previous case (Fig. 3), which can be linked to the increased amount of plastic deformation of the alloy at higher cutting speed. From the above discussion, it can be said that uncoated carbide tools are greatly affected by adhesion and abrasion (irrespective of the cutting speed) during dry machining of nickel-based superalloys.

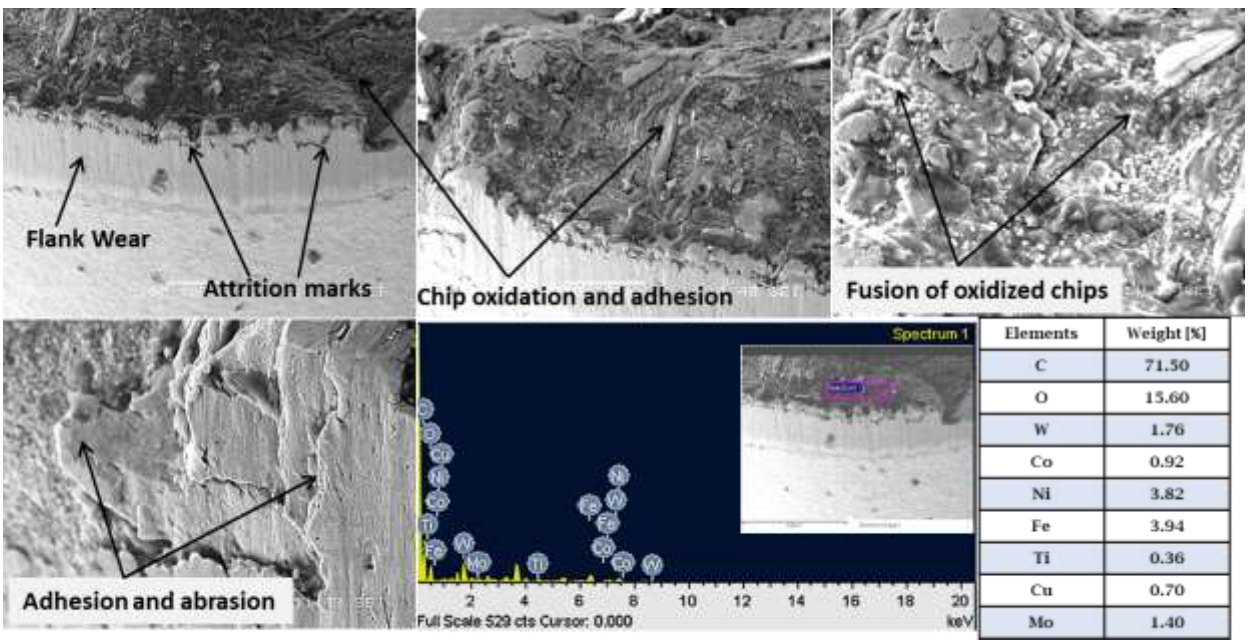


Fig. 4. Wear mechanisms as observed in worn-out uncoated insert (V = 112 m/min).

The bi-layered coated carbide insert is discovered to be affected by coating delamination and tool notching in addition to abrasion, adhesion, and chip sticking at 65 m/min (refer to Fig. 5). Multiple notches are noticed over the cutting edge. Abrasive action of the machined surface together with removal of tool material at depth-of-cut line causes notch wear. Notch wear is a combined mode of failure affecting flank as well as rake surface. Formation of grooves on cutting edge (by rubbing action of work material on tool face at depth- of-cut line) and severe lateral deformation by chips contribute towards notching [19]. Both the flank and rake face of the coated tool are seen to be suffered from material adhesion. Coating starts delaminating due to sudden impact of cutting force acting between tool and workpiece. Moreover, inadequate adhesion over tool face and residual stresses acting on sharp edges of the tool favour delamination to incur [3]. Coating delamination may also take place due to lack of compaction in tool material, improper chemical bonding between tool substrate, and coating material, and presence of inadequate thermal shock absorber. Removal of coating layer not only takes place at rake face but also over flank surface. Excessive abrasion combined with adhesion, detachment of adhered layer, formation of notch, etc. does play a significant role in delamination of coating layers.

Fig. 6 portrays severe crater wear due to formation of a deep crater (through coating dissipation) at rake face of the coated tool at 112 m/min along with material adhesion at cutting edges, tool notching and sticking of chip fragments. Severe delamination of the upper coated layers can be attributed to a sudden rise in cutting zone temperature at this cutting speed. Large and deep crater is, thus, formed spreading over considerable portion of the rake face. As explained by Ezugwu and Okeke [20], coating removal is caused probably by combined action of abrasion, and adhesion. Afterward, oxygen-dominated wear mechanisms become active which rapidly wears out tool substrate by exposing it outside. Elemental analysis on tool rake face adjacent to the formed crater area, shown in Fig. 7a, revealed existence of majority of the elements (like Ti, N, C, O, Al, etc.) that constitutes the upper bi-layered coating system i.e. outer Al_2O_3-layer and inner TiCN-layer. When tool substrate is exposed by removal of the coated layers, it hampers the desired lubricity and antifriction properties of the cutting tool. Thus the coated tool starts acting like the uncoated tool assisting in generation of excessive cutting heat at the tool edge. If the inner coating is not sufficient enough to resist the cutting heat; heat penetrates into the substrate, and weakens the tool. EDS analysis, made at exposed tool substrate over rake face exhibits 49.85% (by weight) of tungsten (W), 33.10% (by weight) of carbon (C), and 2.35% (by weight) of cobalt (Co), which are nothing but the substrate elements of the carbide tool (refer to Fig. 7b). This clearly confirms phenomena of coating delamination exposing tool substrate of the used cutting insert. As the coating is removed, the exposed tool surface becomes a suitable platform for the sticking of ductile chip fragments. As explained by Ahmed et al. [21], substrate exposure resulting from coating dissipation may cause severe chipping and micro-chipping. Due to high temperature, induced internal stresses increase thermal load, and adversely affect thermal stability of the tool. Also, tensile residual stresses are induced during the CVD process as the tool cools down after deposition, mostly because the substrate and coating have different thermal conductivities. Thermal loads are raised and thermal stability is decreased as a result of high tensile residual stress (~ 439 MPa), which in turn might initiate formation of thermal cracks at the coated layers. This peculiarity of CVD-coated tools (thermal instability of coated layers at high temperatures) is to be kept in mind during their usage for machining of high-strength difficult-to-cut alloys.

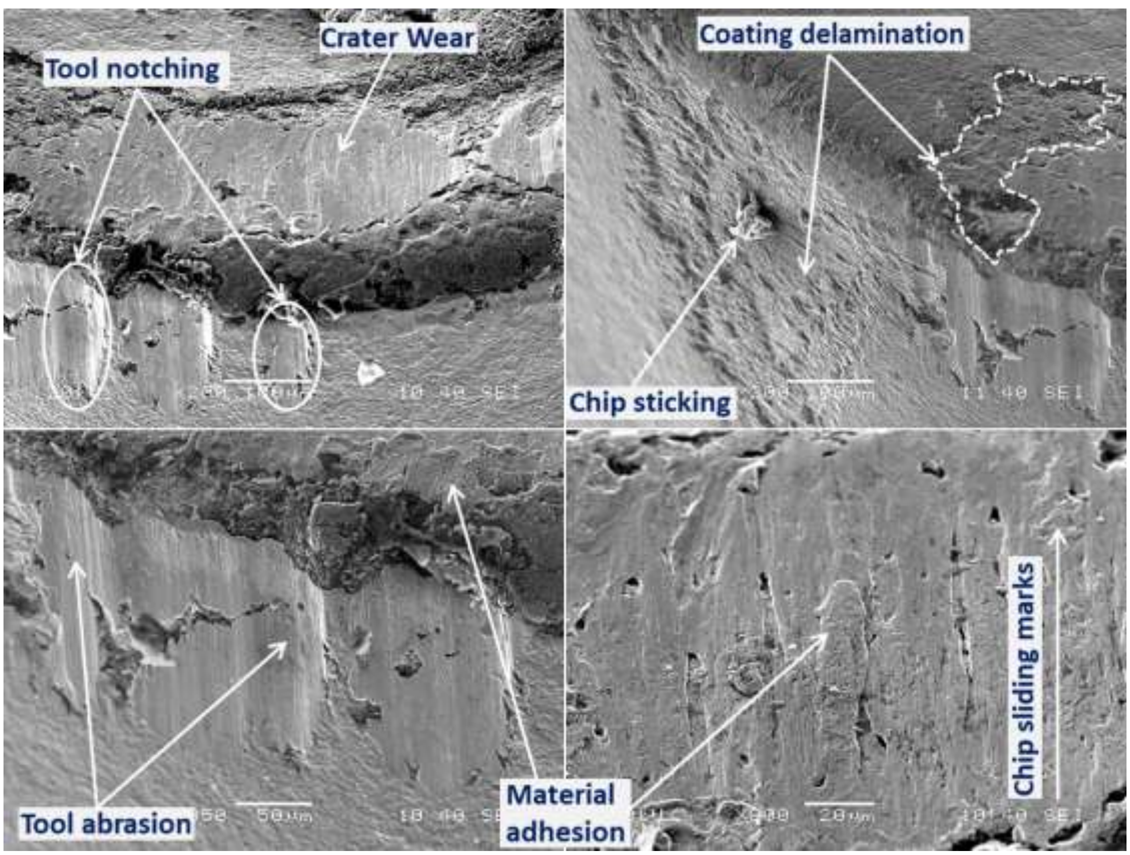


Fig. 5. Wear mechanisms as observed in worn-out coated carbide insert (V = 65 m/min).

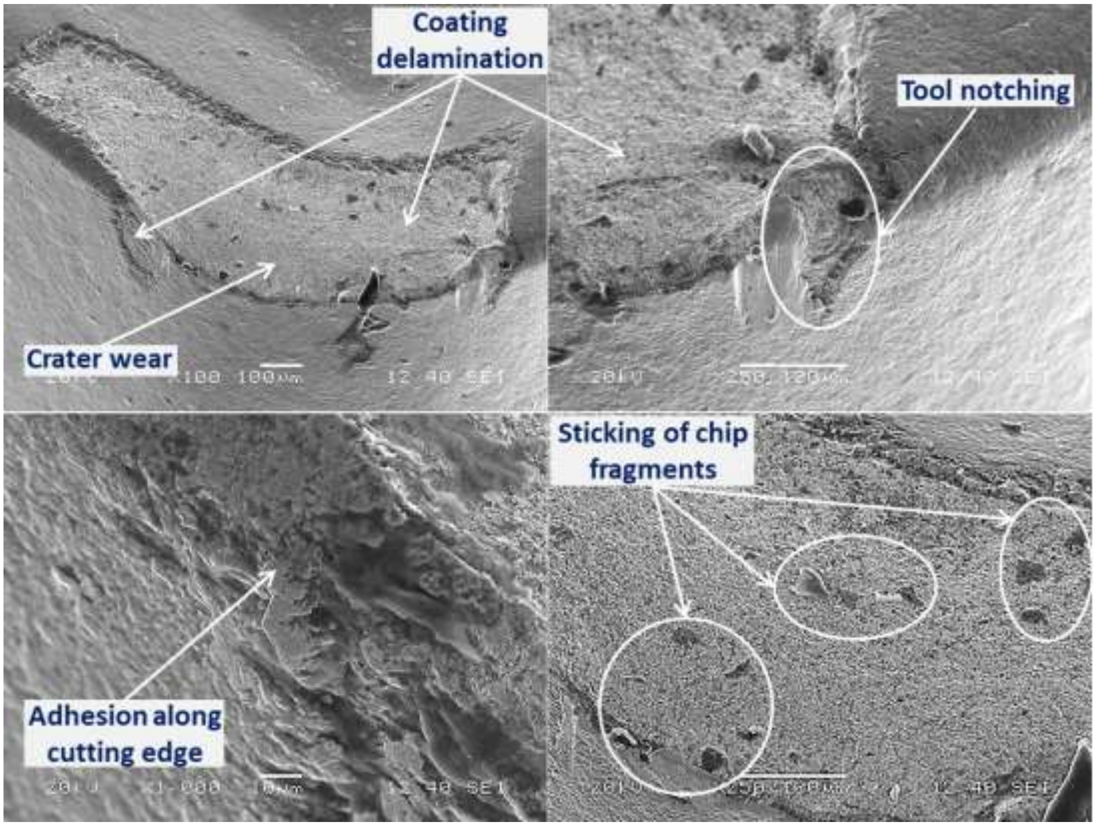
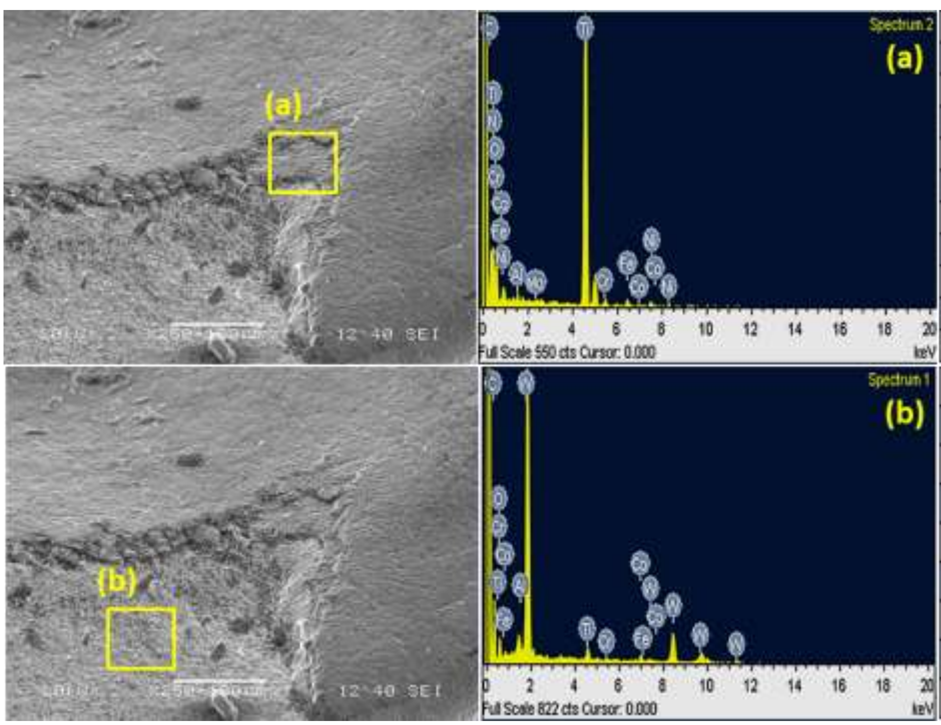


Fig. 6. Wear mechanisms as observed in worn-out coated carbide insert (V = 112 m/min).



Elements	Weight [%]
Ti	27.38
C	28.19
N	22.61
Al	0.40
O	17.78
Ni	1.35
Cr	0.89
Fe	1.14
Mo	0.16
Co	0.11

Elements	Weight [%]
W	49.85
C	33.10
Co	2.35
Ti	2.24
O	11.49
Al	0.32
Fe	0.34
Cr	0.32

Fig. 7. EDS analysis for (a) upper coating materials, and (b) exposed tool substrate (V = 112 m/min).

4. Conclusions

- Material adhesion, tool abrasion, and attrition are found to be dominating wear modes for uncoated carbide insert where the flank wear is severe and much prominent at highest cutting speed (~ 112 m/min). Apart from this, due to huge cutting heat at the tool-chip interface, the evolved chips get oxidized and are fused at tool rake face.
- Even though coating delamination is the most common wear mode noticed for coated tools, adhesion and abrasion are also frequently found. At highest cutting speed flank wear is not significant as in case of uncoated tool but rake face is observed to be affected severely by coating removal and thus tool substrate is exposed to outside.
- The machining gains in case of coated tools employed for high-speed dry machining of Inconel 825 super alloy can be understood from the reduced material adhesion at the tool surfaces and absence of oxidized fused chips. This clearly indicates that less heat evolved at the cutting zone and hence the frictional properties of the coated layers can be confirmed.
- Thermal instability of coated layers at high temperatures can be stated as the root cause of coating delamination in case of coated insert, which is to be considered and monitored further for better machining gain during dry cutting of difficult-to-cut alloys.

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