

Effect of rake face surface of cutting tool on tool crater wear

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Abstract. Tool wear is complex to predict due to the intricate environment of a machining process. However, there are a confrontational effect of tool wear on the machining process in terms of deprived surface finish, reduced dimensional accuracy and increased power consumption. In this study an attempt is made to examine the effect of rake face surface of the cutting tool on tool crater wear. For this, three different types; uncoated, coated and structured rake face cutting tools were used and cutting test were performed of plain carbon steel (AISI/SAE 4140). The cutting speed of 283 m/min, feed rate of 0.1 mm/min and depth of cut of 0.1 were used. Results show, structured rake face of the cutting tool benefitted most in supressing the tool crater wear. Energy-Dispersive X-Ray analysis (EDXA) analysis confirms reduction in iron transfer on tool rake face in case of coated and structured cutting tool. Micro – hardness test was also performed and the values in case of coated and structured cutting tool was found to be suffice. This study can be a benefit for cutting difficult to cut material where crater wear formation is unavoidable.

Keywords: Crater wear / wear pattern / structured tool and machining

1 Introduction

Surface integrity of the machined work piece is significantly dependent on the tool wear. To optimize the cutting process, studies have been conducted to improve the performance of cutting tools in-term of increased wear resistance and anti-adhesive properties by altering the tool geometry, tool materials, surface finish and surface coating [1]. In the metal cutting elevated temperature and high value of both normal & shear stresses between the tool and work piece material at the cutting edge contributes to the development of tool wear. During the process, the nascent surface becomes extremely chemically active because of thermo-mechanical load and due to the absence of nitride and oxide layers on the surface. This condition contributes to the specific type of tribological phenomena at tool chip interface and contributes in abrasion, adhesion and chemical reactivity of a tool. Till date, the tool wear is control by altering the tool material, coatings, cutting parameters and cutting temperature [2,3].

The main reason of tool wear is the gradual loss of material from the tool, which leads to flank and crater wear. Abrasion wear between the flank face adjacent to cutting edge and newly generated work piece contributes to the flank wear [4]. During the cutting operation, residual

stresses are also increased towards higher tensile stresses and results in increasing flank wear [5]. Whereas, Crater wear in a cutting process is developed by the contact and the relative sliding between chip and rake face of the tool. Under the extreme condition of cutting area, where temperature exceed 900 °C [6] and pressure of 2000 psi [7], any changes to the contact condition can affects the tool crater wear. It is recognised that the surface at/or near the cutting edge has to be hard enough to resist abrasion and chemically stable to create a barrier for diffusion between to tool and work material. Generally, crater wear is reduced by selecting appropriate cutting parameters and using coated tool.

To reduce the tool wear, particularly the crater wear, researchers have carried out intensive research on coated carbide tools. Categorization of coated carbide tools with respect to cutting forces and the reduced tool wear has also been established [8]. Research has been conducted on wear resistance coating system of Titanium (Ti), Chromium (Cr), Aluminium (Al) and Silicon (Si) for increasing the performance characteristics of cutting tools [9]. The type of coating and structure of the coating also plays an important part in displaying desirable cutting tool properties (wear resistance, thermal conductivity and oxidation). Also, role of elemental composition of coating is extremely significant in the formation of crater wear [10]. Avila et al. [11] conducted 3D topography technique to evaluate the crater wear volume for different types of

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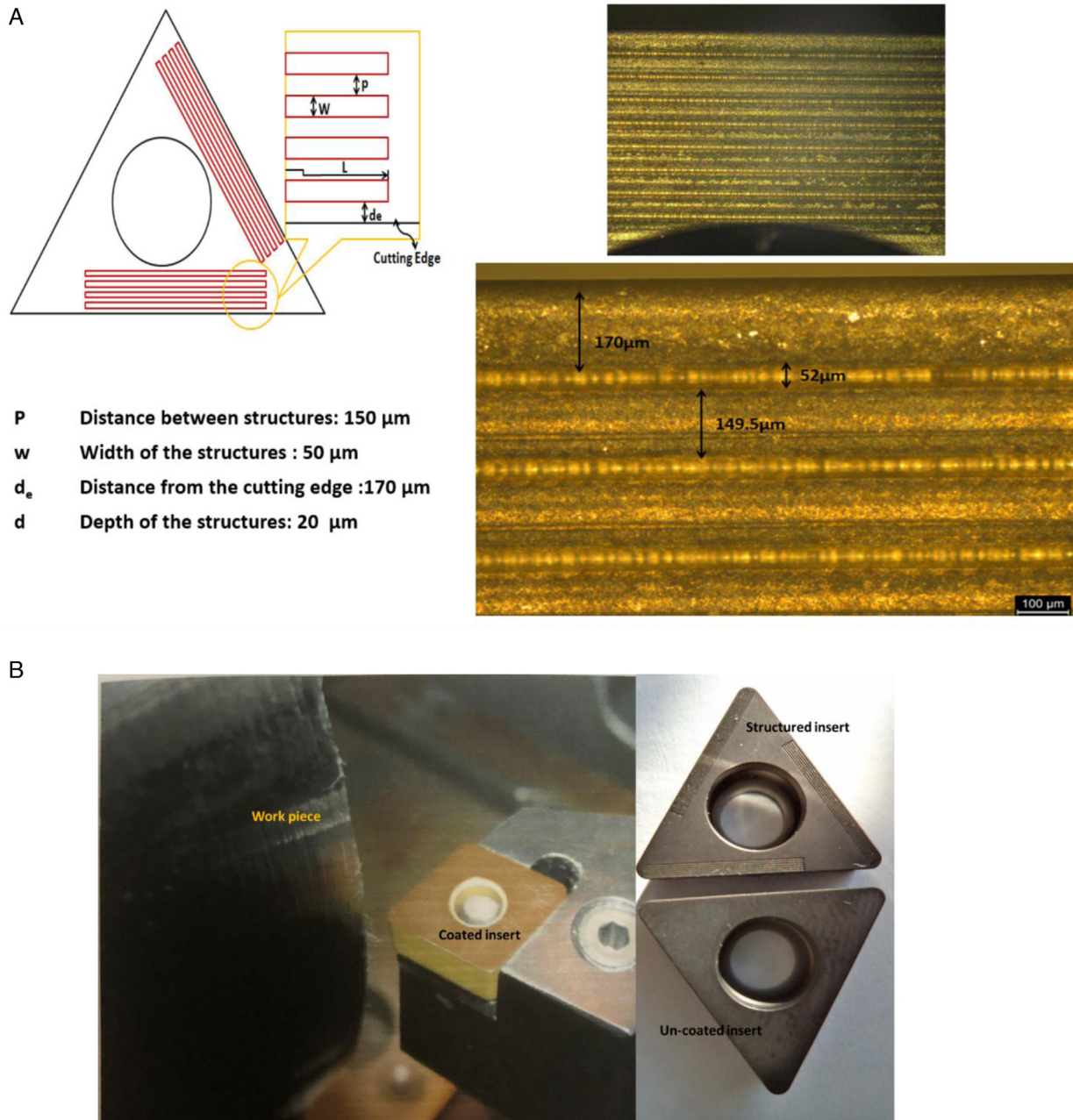


Fig. 1. (A) Structures profile; (B) Cutting inserts.

coating films [Ti-N, (Ti,Al)N & Ti (C,N)] on cemented carbide inserts. The study was considered on AISI 4340 work piece material. Results suggests high rate of crater wear in TiAlN coated carbide tool due to the presence of aluminium, causing low toughness has contributed to greater wear. Wang et al. [12] inferred that (Cr,Ti,Al)N coating significantly produce better results in achieving high hardness and crack resistance among other type of coating. It was explained that titanium-based coating showed exceptional results; high wear resistance and hardness properties even at elevated temperature during the machining operation. TiN demonstrate excellent

chemical stability under high temperature (above 750 °C). This is due to the presence of intermediate coating of oxygen, aluminium and nitrogen and outmost protective coating layer of Al_2O_3 that develops higher oxidation resistance during machining operation. Devillez et al. [8] and Stappen et al. [10] concluded that TiN coated tools shows resistance to crater wears due to lower thermal conductivity which leads to lower temperature of tool-tip and chip interface. It was noted that Devillez et al. [8] perform experiments in laboratory setup while Stappen et al. [10] were performed experiments in industrial environment.

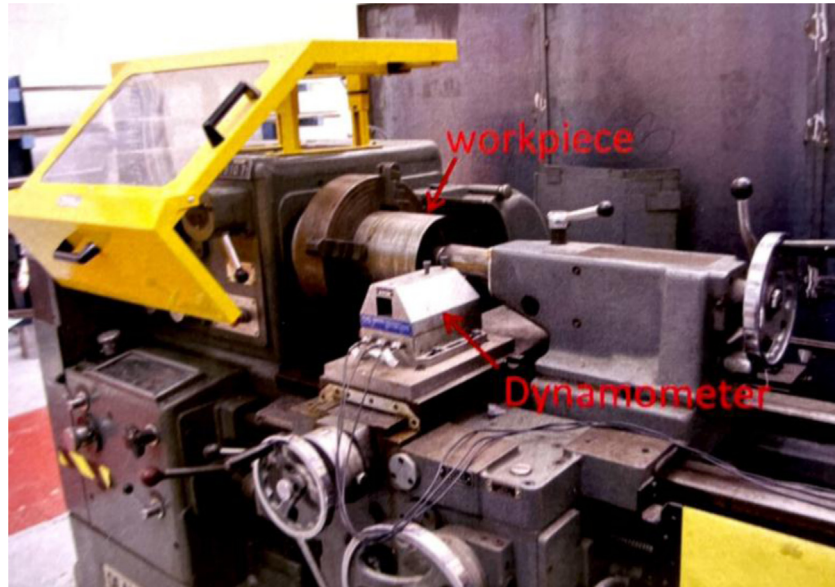


Fig. 2. Experiment setup.

To improve the life of cutting tools, surface structuring techniques on the rake face of the tool is a popular trend and has evident improvement in tribological phenomena at tool and chip interface. Chang et al. [13] used femtosecond laser technology to develop the stripe-grooved surfaces on the tool flank face those results in considerably reduced flank wear. The focus of research was to identify the orientation of created structures on cutting tool to reduce tool wear. Ze et al. [14] investigates the effect of structures on the cutting tool with respect to structures dimension under wet and dry cutting conditions. It was found that flank wear can be greatly reduced with decreasing structures dimension. Enomoto et al. [15] create grooved structures on TiAlN-coating insert and test its performance on aluminium alloy and steel alloy for the face milling operation. Grooves were $5\text{ }\mu\text{m}$ deep and $20\text{ }\mu\text{m}$ apart and was generated by femtosecond laser on the rake face of cemented carbide cutting tool. Results of the study showed that chip adhesion was significantly decreased. Same results were obtained by Sugihara et al. [1] in dry cutting of medium carbon. However, it was noted that both research study was focus on the orientation and density of structures on rake face rather than tool wear. Fatima et al. [16] while optimising the machining process for structured cutting tool observed that structured cutting tool develop less flank wear than traditional cutting tool. Zou et al. [17] studied the performance of structured tool in machining of inconel 718 alloy and identified that tool life was increased by 23% in comparison to traditional tool.

Research motivation

Till date intensive research has been conducted on cutting performance of structured tool and only limited studies are available on tool wear. Previously, researchers have compared performances of structured tools with respect to cutting forces, tool temperature, chip morphology and tool life. In this study, a detail analysis of tool crater wear is

conducted. For this, structures on rake face of the cutting tool were created through lasers and its wear reducing performance is compared with coated and uncoated cutting tools. Results of this study can be a benefit for cutting difficult to cut material where crater wear formation is unavoidable.

2 Material and methods

AISI/SAE 4140 plain carbon steel was used as a work piece material (diameter 77mm and length 130 mm) and commercially available uncoated (TCMW 16T308 CT 5015) and TiN coated (CNGA 120404S01525H 7105) Sandvik carbide inserts were employed. TCMW 16T308 5015 was carefully selected as it was uncoated and also flat rake surface that allows easy fabrication of structures. It was also compliant to the work piece used in this research. Whereas, CNGA 12040S01525H 7105 was selected as it is a top-level coated tool that gives enhance crater wear resistance. Micro structures were made on rake face of TCMW 16T308 CT 5015 insert, using diode LASER (light amplification by stimulated emission of radiation) system. Laser cutting parameter were used as specified by Fatima et al. [18]. Structures dimensions were selected in accordance to the research study by Fatima et al. [19]. Structures were created with the error of $\pm 5\text{ }\mu\text{m}$ and their profile is shown in Figure 1A and insert used in this study are shown in Figure 1B. While, experimental setup is shown in Figure 2. Cutting experiments were performed on computer numeric control (CNC) lathe by MHP (MT-50 MDSI open CNC). The cutting speed of 283 m/min, feed rate of 0.1 mm/min and depth of cut of 0.1 mm were used in accordance to the manufacturer's recommendations. Machining time for each experiment was approximately 60 min and experiments were repeat randomly three times. For each experiment a new cutting tool was used. SYN 30, by Callington was used as a coolant. Wear characterisation

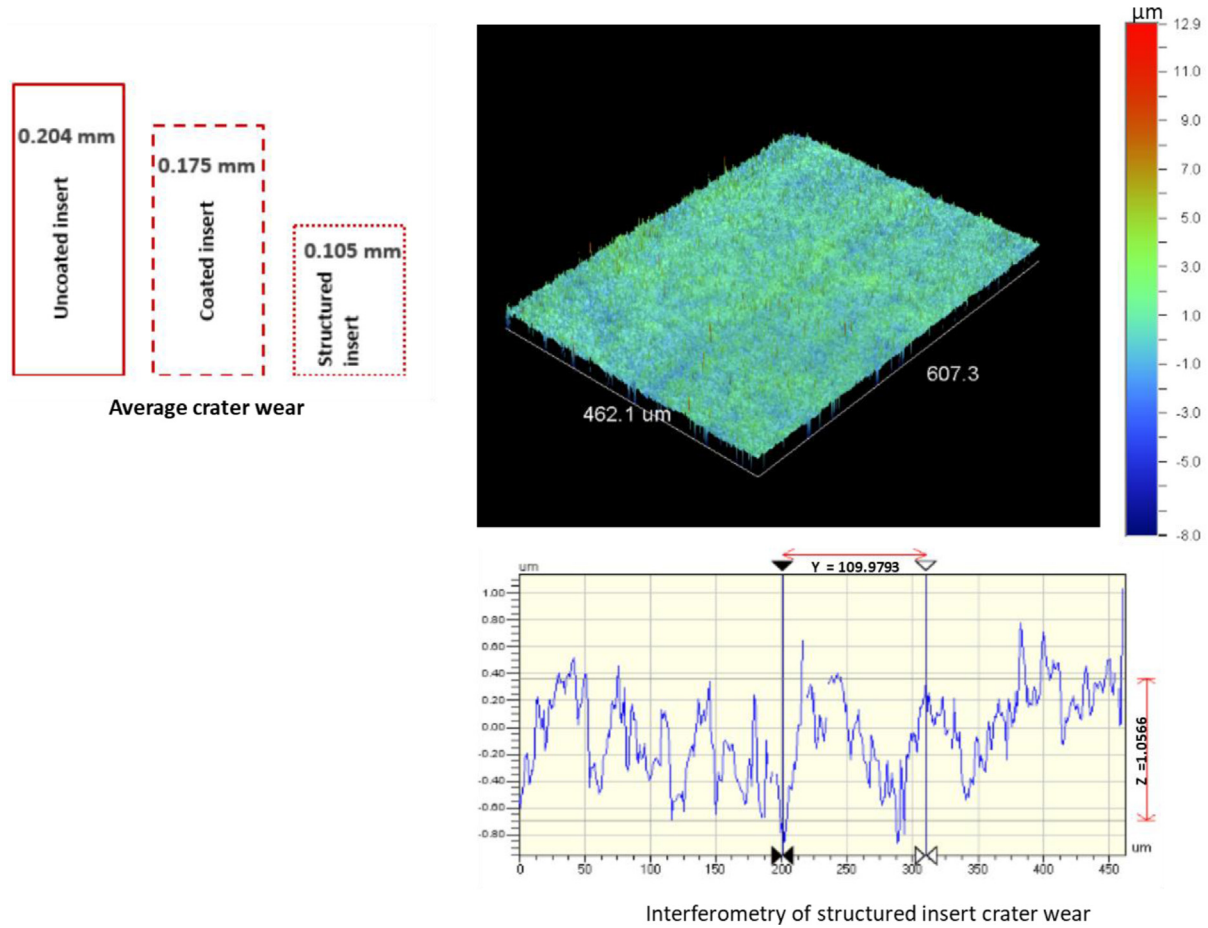


Fig. 3. Sample crater wear measurement.

was performed on stereo microscope. Quantification of iron contents was obtained through scanning electron microscopy, energy dispersive x-ray (SEM EDX) analysis. Wear depth was measured by Wyko NT1100 white-light interferometer. Micro hardness tests on inserts rake face were conducted on NOVA 130/240 series using 2 kgf load for 30 sec.

3 Result and discussion

Crater wear is due to chemical reaction between tool and chip material. It is established that over a tool rake face, near the cutting edge the phenomenon of sticking contact exists while the remaining contact is sliding. Over sticking contact, frictional stresses are constant (hence seizure occurs) whereas on sliding, coefficient of friction is constant [20]. The contact temperature and coefficient of friction controls the level of diffusion over the contact [21].

For this study, the depth of crater of was measured using white light interferometry [22] and an average value is shown in Figure 3. While, Table 1 shows the experiment results. This technique is established in measuring surface heights on 3D surfaces with the profile that vary between the micrometres and nanometres [23]. The reference and the test (sample) surface are illuminated by the light beam. Since light has the coherent property, the interference signals are produced

between the light and that scattered from the sample surface and the reference surface. The returning beams are recorded to form an interferogram, which is process by the computer and use to analysed data, such as 2D roughness height, peak to valley height and 3D height maps as shown in Figure 3. Such multiple measurements were made and average value was recorded. Crater wear for uncoated insert was 0.204 mm, for coated insert it was 0.175 mm and in case of structured insert it was 0.105 mm. Initially, crater wear progressed due to the abrasion, resulting in increasing friction at tool chip contact. High friction amplified the temperature and this facilitates the thermal softening of the work material. The hard constituents of the work material eroded/diffused into the chip material thus increasing the crater wear. Moreover, Che Haron [24] researched that insert with smaller grain size wear more rapidly due to increase solubility of carbide particles. In this case, un-coated inserts have a grain size of 1.3 microns and coated inserts has a grain size of 2 microns. Also, for coated insert, the coating has reduced the related phenomena and has slow down the propagation of crater wear. In case of structured insert, structures have reduced the contact and have consequently reduces the tool temperature thereby delaying the formation of crater wear. Moreover, structures are treated as micro reservoir of coolant from where the chemically reactive surface layer of adsorbate is formed [16]. This helps in reducing the interface temperature by prohibiting the direct contact at the interface.

Table 1. Experiment results.

Time (min)	Avg. Crater wear (mm)											
	Uncoated @ V_c 283 m/min				Coated @ V_c 283 m/min				Structured @ V_c 283 m/min			
	Average trial 1	Average trial 2	Average trial 3	Total average	Average trial 1	Average trial 2	Average trial 3	Total average	Average trial 1	Average trial 2	Average trial 3	Total average
60.00	0.204	0.189	0.220	0.204	0.186	0.174	0.164	0.175	0.109	0.102	0.104	0.105

3.1 Wear topography

Figure 4 shows the wear topographies of worn inserts. For the plain surface insert, the wear happens in a form of crater, developed at the cutting edge. A plastic deformation of the cutting edge is also observed. This type of wear pattern indicates the development of high temperatures gradients at the vicinity of cutting edge [25]. High temperature disturbs the hardness of the cutting tool which softens the surface and as a result aggressive abrasion creates a crater. For fine grain tools, high temperature also results in plastic deformation, diffusion and adhesion that contributed in crater formation. For coated tool, it is revealed from optical image that the wear on the rake face was a result of abrasion by the chip flow. It can be noted that chip material/wear debris (shiny surface) is adhered due to high temperature at tool rake face. Aslantas et al. [26] explained that as the cutting time progresses the temperature of the tool is increased. The high temperature tempers the tool coating strength and thus the coating material is diffused into the underside of chip and weakens the matrix of coating. In this case, the presence of diffusion is obvious by erosion/chipping at the edge (observed in flank wear image). Oxidation of surface coating is also evident through bluish colour. Since, the experiments were performed in an open atmosphere, there is a probability that oxygen from atmosphere diffused into the tool and/or underside of chip and has contributed in wear. Whereas, on flank face for plain and coated rake surface, the wear develops due to abrasive action and it was uniform. It is established that structures on the rake face act as coolant reservoirs and sites to trap debris [1]. As cutting fluid does not reach cutting edge due to high pressure vortex formation, structures deliver coolant to the cutting edge during the cutting process [1]. This benefits in lower cutting temperature and reducing friction at the rake surface consequently, reducing the mechanism of adhesion, diffusion and attrition. However, the hydrodynamic action of the coolant initiating from structures has expedited chip curl early and has pushed the chip towards flank face. This has aggregated the abrasion and adhesion mechanism at the flank face.

3.2 Iron quantification

It is well formed that iron quantification on the rake face identifies the adhesion phenomenon [27]. It also identifies the presences of sticking and sliding region on rake face [28]. Higher concentration of iron identifies sticking contact and

this also indicates the region of higher temperature gradients [28]. Figure 5 shows the scanning electron microscopy image of structured tool and the scanned lined where the iron quantification was measured. Similar line scan was performed on all tested tools and the criteria to select the line close to the edge is as follows: Fatima et al. [19] identifies that structures should cover the 45% contact area and should be located away from the cutting edge for optimum machining performance. Moreover, it is established that machining with the conventional tool forms the sticking zone close to the cutting edge, which is responsible for the crater wear. Figure 6 shows the scanning electron microscopy, energy dispersive x – ray (SEM EDX) iron quantification of worn inserts. Scanning electron microscopy, energy dispersive x – ray (SEM EDX) was performed on Philips XL 30 FEGSEM.

The average weight percentage of iron transfer on plain rake surface insert was 30%. This signifies the occurrence of adhesion. Also, it is noted that the higher concentration of iron is near the cutting edge, highlighting the location of crater formation. In case of coated rake surface insert, the average weight percentage of iron transfer was 22%. The concentration of iron transfer was almost uniform along the rake face indicating that the different wear mechanism is occurring instantaneously. For structured rake face insert the average iron weight percentage was 17% and the iron concentration was concentrated on the structured site. This highlights two effects of structured rake face surface of insert: 1) the debris entrapment function of structures and 2) it has suppressed the formation of crater wear by reducing the adhesion, diffusion and abrasion mechanism.

3.3 Micro-hardness

Micro hardness test is an effective technique to judge the consequence of strain hardening [29]. The samples were washed in ultrasonic tank for 3 min in plain water and the hardness test was performed randomly on the rake surface of the tool near the cutting edge and the contact area. Figure 7 represents the location on rake face of the cutting tools for the hardness test. Figure 8 shows the results of micro hardness test. The average micro hardness value of rake face of plain and structured inserts was 26.53 GPa. For coated insert the average value of micro-hardness of rake face was 34.95 GPa (more appropriately coating hardness). After cutting tests the percentage decrease in micro hardness of plain insert was 18.3%, 11.4% for coated insert and 12.2% for structured insert.

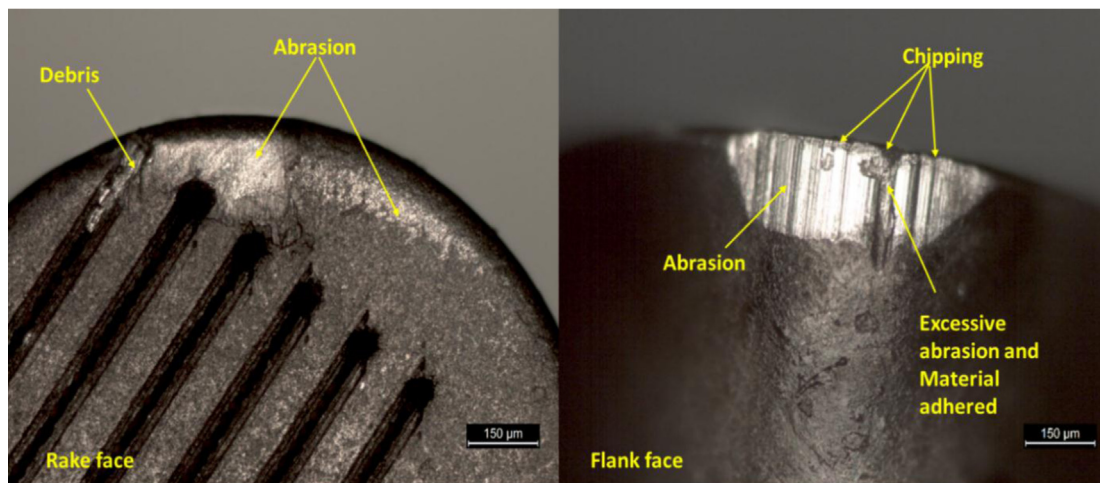
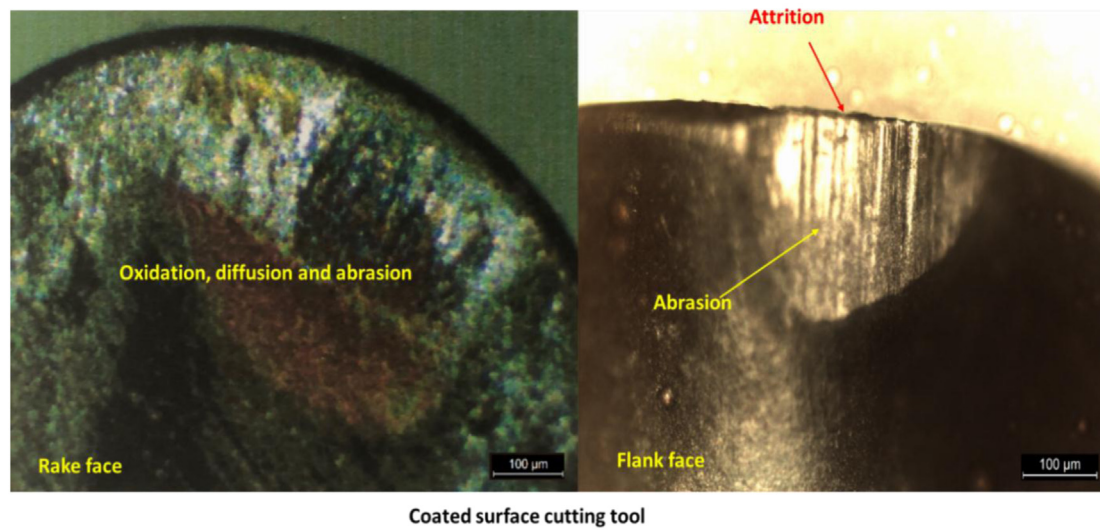
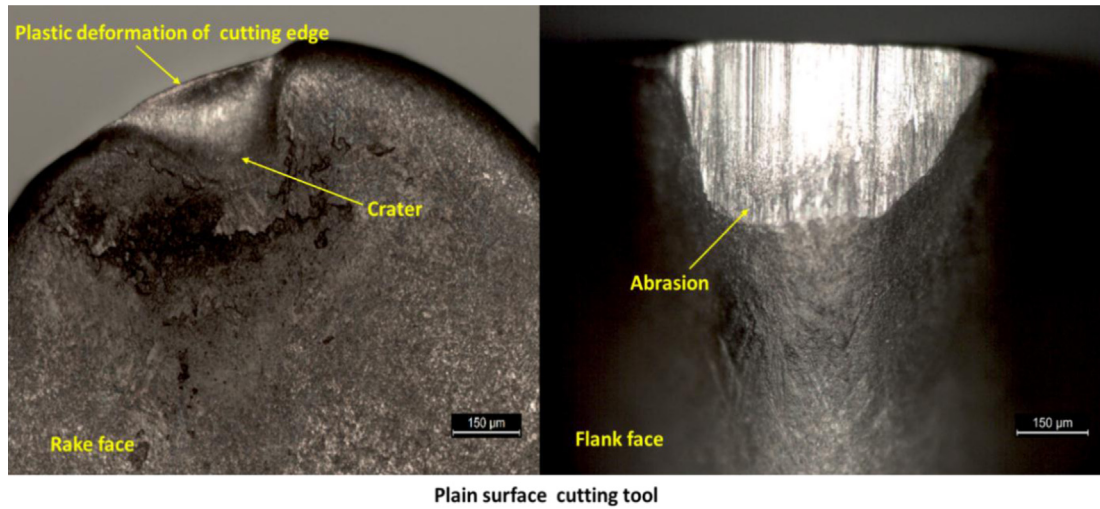


Fig. 4. Wear topography.

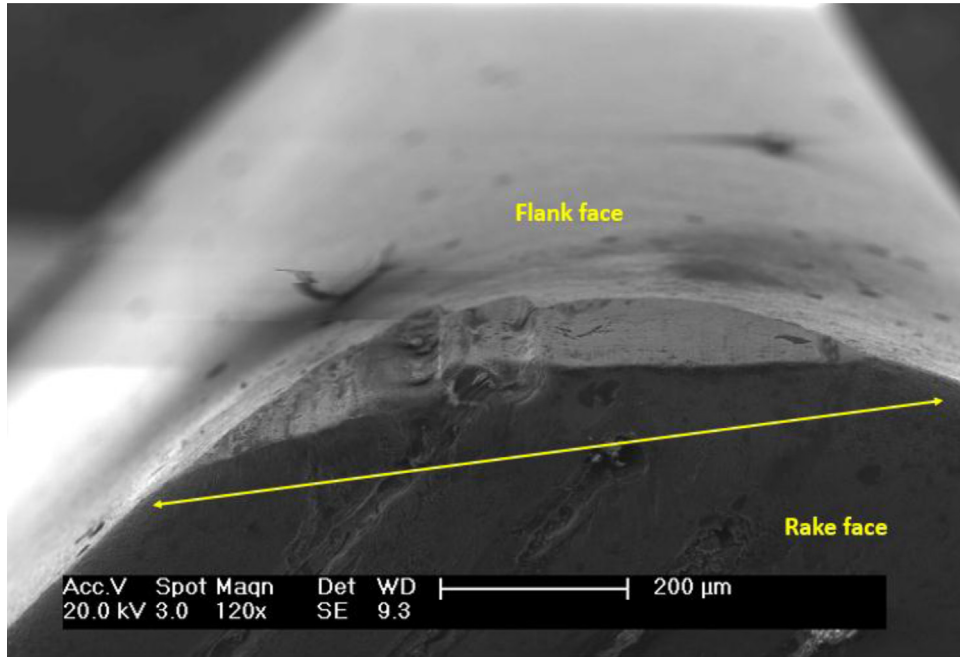


Fig. 5. Scanning electron microscopy demarcation for iron quantification of structured tool.

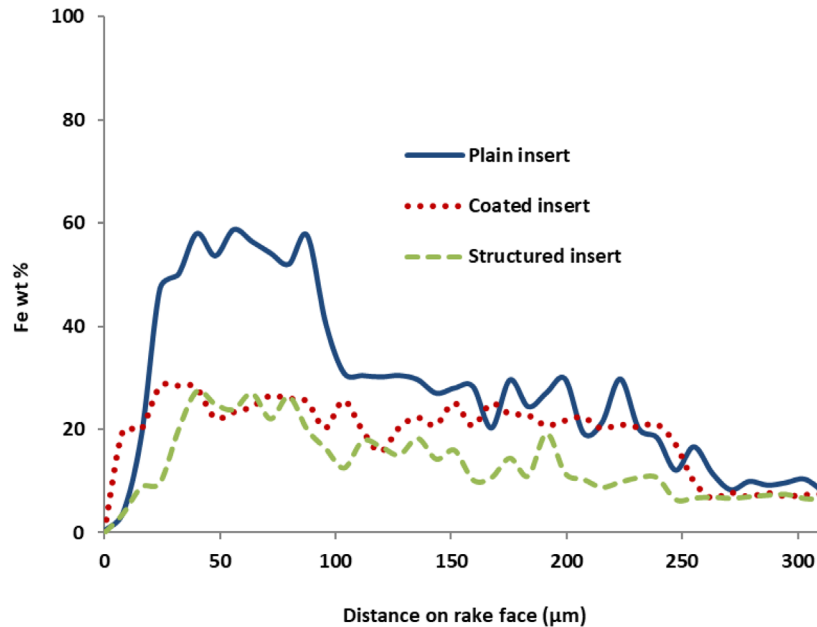


Fig. 6. Iron quantification.

In case of plain rake face insert, the drop in hardness could be a result of yielding of a binder material and carbide grains at the surface due to the chip flow [29]. The compressive and frictional stresses at the tool chip contact might have altered the surface matrix of the insert. Whereas, for structured insert the laser ablation has altered the grain structure of insert that has subsidised the hardness (wear resistance property) of the insert [18]. Grigoriev et al. [30] on TiN

coating wear process explained that wear pattern of coating is brittle in nature with chipping of fragments of coating material. It was further explained that delamination between the layers of coating was also observed however, delamination does not transfer in to longitudinal cracks. Such delamination reduces the level of stresses and display positive part in slowing the wear. This description explains the minimum decrease of micro hardness in coated inserts.

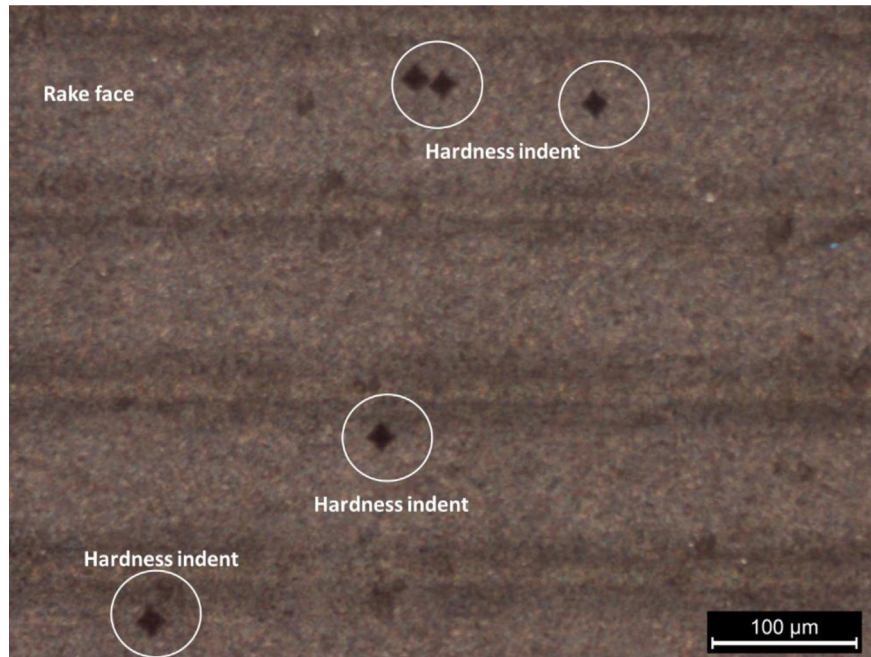


Fig. 7. Hardness test location.

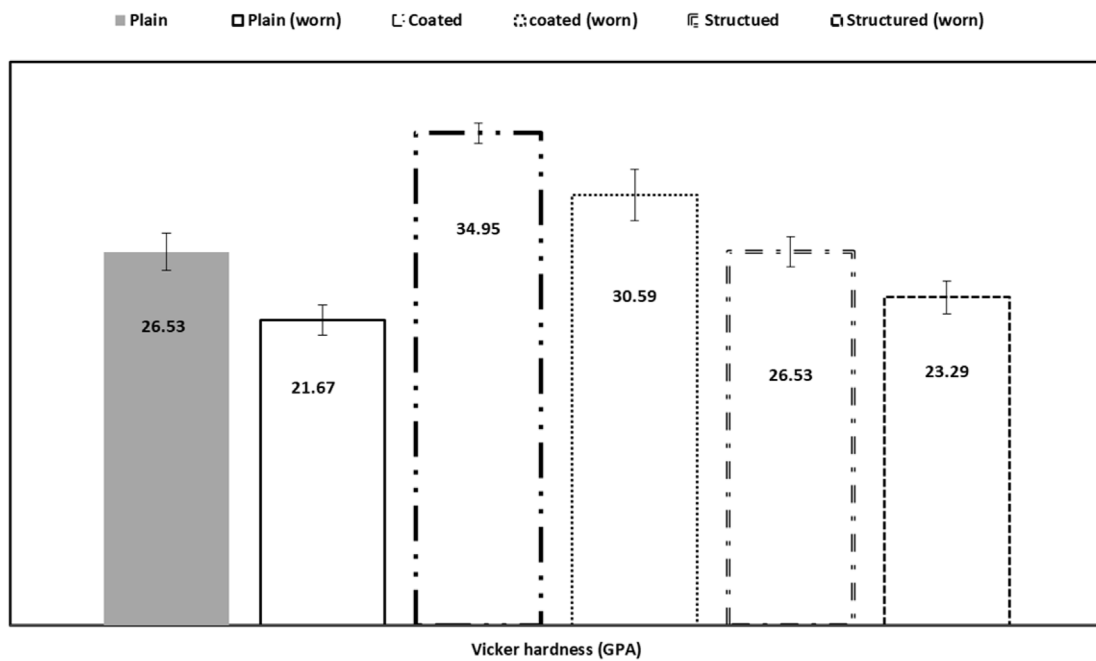


Fig. 8. Micro hardness.

4 Conclusion and future outlook

In this study, the effect of rake face surface on tool crater wear was examined. For these three different rake face surfaced tools (uncoated, coated and structured) were utilised in cutting experiments and following conclusions were drawn:

- For uncoated rake face cutting tool crater wear was 0.204 mm, for coated rake face surface it was 0.175 mm. in case of structured surface crater wear was minimum with the value of 0.105 mm. Structures at rake face site act as a cutting fluid reservoir and also the site to trap debris. This action of structures has helped in reducing the crater wear formation.

- Energy-Dispersive X-Ray analysis (EDXA) analysis revealed that the structuring the rake face has significantly modify the tool chip contact phenomenon in term of sticking contact by reducing the iron transfer. It was found that in case of structured tool iron content was reduced to 17 % from 30 %.
- Hardness of the cutting tool is a key parameter to characterise surface integrity of the artefact. Micro hardness analysis shows that the percentage decrease in hardness of the cutting tool was observed for all three selected inserts. The percentage decrease was minimum in case of coated tools. Since it is established that coating application on a cutting tool is relatively expensive technique therefore, it is recommended to take a competitive advantage by structuring the cutting tools. Structuring the rake face surface of the cutting tool is more beneficial in term of wear resistance and in maintaining the tool micro hardness.

Declaration of interest statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Moreover, the authors declare that they have no known competing interests for the publication of this paper. All author gives full consent for publication.

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