Journal of the Brazilian Society of Mechanical Sciences and Engineering (2018) 40:450
https://doi.org/10.1007/s40430-018-1379-y

TECHNICAL PAPER

Influence of coconut oil on tribological behavior of carbide cutting tool insert during turning operation

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Received: 27 March 2018 / Accepted: 22 August 2018 / Published online: 27 August 2018

Abstract

In manufacturing industries, machining is considered as one of the most significant and effective processes. During machining process, cutting zone experiences the higher temperature due to friction between the chip-tool and work-tool interfaces, which directly influences the tool wear, surface quality and dimensional accuracy of the work material. Even though cutting lubricants are extensively used for lubricating and cooling the tool-workpiece contact area, their application has several drastic effects on environment and the health of operators. Hence, there is a need to identify an environmental friendly and user-friendly alternative to conventional cutting lubricants. The main objective of this work is to evaluate the effect of cutting lubricants on tool wear, friction coefficient, surface quality and chip morphology during turning of AISI 1040 steel with tungsten carbide tool insert under dry, wet, coconut oil, minimum quantity lubrication (MQL) using water-miscible fluid and MQL using coconut oil cutting conditions. The wettability characteristic of coconut oil on a carbide tool insert results in good adsorption on tool and workpiece, which causes effective lubrication and reduction in friction. It was found that the wettability angle of coconut oil is 33.7°, which greatly enhanced the wettability characteristics compared to the conventional cutting fluids. The MQL method using coconut oil machining condition resulted in a significant decrease in tool wear, friction coefficient along with favorable chip morphology and better surface quality of the workpiece.

Keywords Friction · Tool wear · Coconut oil · Cutting lubricants

1 Introduction

In a manufacturing sector, materials are often machined with high cutting speed, feed rate and depth of cut to achieve higher productivity and profitability. This machining generates high cutting temperatures in the cutting zone increasing the tool wear and thereby impairing the quality of products. The cutting zone temperature is controlled by employing cutting fluids. Over the last 200 years, conventional cutting lubricants have been extensively used in machining process playing a vital role in the improvement of the metal-cutting operations [1, 2]. However, as cutting operations became more severe, metal-cutting fluid formulations turned out to be more complex [3]. In most of the manufacturing processes, mineral oil-based lubricants are abundantly used because of their superior lubrication and cooling properties which increases the productivity and the quality of the products [4]. However, the excessive use of mineral oil-based metal working lubricants has several detrimental effects on the production cost, health of the operators and the environment causing soil contamination and water pollution [5]. To overcome the aforementioned challenges, researchers are exploring various alternatives to conventional cutting lubricants. Such alternatives include dry machining, high-

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Technical Editor: Márcio Bacci da Silva.

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pressure coolant techniques, tool coatings, minimum quantity lubricant (MQL), vegetable-based cutting lubricants, etc. With the rapid development of the cutting tool materials, demand for dry machining has attracted a lot of attention in the field of green manufacturing [6–8]. However, it becomes less effective if higher machining efficiency, better surface quality and severe cutting conditions are required. In such cases, MQL is a suitable alternative where a small quantity of cutting lubricants is delivered at high pressure through the nozzle onto the chip-tool contact area. The mixture of soluble oil, along with compressed air, decreases the cutting zone temperature and increases the tool life to some extent. In MQL, only 0.05% of the amount of cutting lubricant is used than that used in wet machining condition saving the cost of lubricant, recycling and filtration and thus leading to economic benefits [9–12].

From the environment, health, cost, safety and performance concerns, vegetable oil-based cutting lubricants are considered a highly attractive alternative for conventional metal-cutting fluids. The vegetable oil not only has high viscosity index, flash point and lubricity but it also has higher molecular weight and boiling point which results in a considerable reduction in vaporization and misting. Moreover, vegetable oil mists do not produce significant organic diseases and toxic effects on humans as reported by the American Conference of Governmental Industrial Hygienists, ACGIH [11, 13, 14]. Though most of the vegetable oils have low oxidative and thermal stabilities [15], these can easily be improved by modifying the vegetable oil base stock using methods like genetic modification of the oil seed crop, chemical modification and reformulation of additives, and by interesterification, transesterification, hydrogenation and epoxidation methods [16]. In MQL machining where a cutting fluid is selected based on its primary characteristic, i.e., the cutting performance and secondary characteristics such as biodegradability, storage stability, thermal and oxidation stability, vegetable oils are preferably used over mineral oils due to their superior cooling and lubricating properties. These cooling properties can be evaluated from the wettability characteristics of the fluids [17, 18]. The rate of heat removal from a heated component depends on the wetting and spreading characteristics of the liquid medium on the substrate. The wettability of a fluid is defined as the contact angle between a liquid droplet and a solid surface, in thermal equilibrium with each other, along with the gaseous phase. Wettability refers to the ability of a liquid to spread out, penetrate and cover the tool and workpiece [19].

A considerable number of studies have been done suggesting that vegetable oil-based lubricants are better alternatives over mineral oil-based lubricants. Stanford and Lister [2] investigated the role of various cutting environments on tool wear while machining an EN 32 case hardening steel material. The comparative cutting trails in the turning process showed a significant reduction in the flank wear under nitrogen rich atmosphere cutting condition on both coated and uncoated tool inserts. Shashidhara and Jayaram [3] reviewed the performance of vegetable-based oils as straight oils and emulsions for machining of various materials under different machining conditions. The environmental friendliness and the biodegradable characteristics of vegetable oil-based cutting lubricants make them promising alternatives for conventional mineral oils. Lawal et al. [4] reviewed the efficiency of vegetable oils as metal working lubricants in machining of ferrous metals. In this work, the performance of biodegradable lubricants was evaluated in terms of wear rate, cutting zone temperature, cutting forces and surface finish of the workpiece. The vegetable oil-based metal working lubricants were found to perform better than the conventional mineral oils. Khan and Dhar [10] investigated the influence of MQL by vegetable oil-based cutting lubricants on tool wear, cutting zone temperature, surface quality and dimensional deviation in turning AISI 1060 steel using uncoated carbide cutting tool inserts. The results obtained revealed a decrease in the cutting zone temperature under MQL cutting condition, thereby causing a substantial reduction in tool wear, surface roughness and dimensional inaccuracy of the workpiece. Khan et al. [11] evaluated the effects of MQL using vegetable oil-based metal working lubricants during turning of AISI 9310 alloy steel. The authors reported a substantial decrease in temperature at the cutting zone.

Babur et al. [13] studied the performance of canola and sunflower oils by adding 8% and 12% of extreme pressure (EP) additives and compared them with two commercially available cutting lubricants. The combination of 8% EP additives and canola oil showed better machining performance by reducing cutting forces, tool wear and surface roughness values. Mannekote and Kailas [16] carried out experimental studies on the long-term aging effect on coconut and soybean oils at elevated temperature. An increase in wear was observed with the aged coconut oil and soybean oil samples due to the formation of peroxides and destruction of triglyceride structure. The analysis of the results showed that the coconut oil has a better storage life and lubrication properties than that of soybean oil. Xavior and Adithan [20] experimentally investigated the performance of various cutting lubricants viz. straight cutting oil, soluble oil and coconut oil during turning of AISI 304 stainless steel using cemented carbide tool inserts. The relative performances of these oils were evaluated in terms of reduction in tool wear and surface roughness on the workpiece. The results highlighted a comparatively better cutting performance of coconut oil than that of the conventional mineral oils. Belluco et al. [21] assessed the efficiency of five vegetable oil-based cutting lubricants during drilling of AISI 316 L austenitic stainless steel. The mineral oil-based cutting fluid was taken as the reference cutting fluid. The process parameters such as cutting forces, tool wear, tool life and chip formation were evaluated in the results, which showed that all vegetable oil-based cutting lubricants performed better than the mineral oils. Kamata and Obikawa [22] compared the performance of three different coated carbide tools under dry, wet and MQL machining environments during machining of Inconel 718. The cutting tool life and surface finish of the workpiece were considered to evaluate the effectiveness of cutting environment and the type of carbide tool. The results revealed that the MQL plays a vital role in cooling the cutting point and TiCN/Al_2O_3 carbide tool exhibited the best machining performance under MQL cutting environment.

Obikawa et al. [23] evaluated the micro-liter lubrication performance of a specially designed nozzle and an ordinary spraying nozzle during machining of Inconel 718. The results revealed that an increased tool life was obtained with the specially designed nozzle and it was quite effective in the micro-liter lubrication range. Sharma et al. [24] presented a brief overview on the major advances in cooling techniques such as solid lubricants, compressed air, cryogenic cooling, high-pressure coolant (HPC) and minimum quantity lubrication. From the analysis of all these techniques, it was concluded that the productivity of the process can be greatly enhanced by the implementation of the above-mentioned cooling techniques. Bin Li et al. [25] carried out experimental investigations on the ceramic cutting tool insert under air and nitrogen atmosphere during turning of AISI 1045 steel. The evaluation of results revealed that the tool wear, friction coefficient and cutting force were greatly reduced in air atmosphere due to the formation of oxide layer between the chip-tool interface which enhanced the machining performance compared to that of nitrogen. Chandra Nath et al. [26] carried out experimental studies to investigate the effect of five different concentrations of metal working fluid on cutting force, tool wear, tool life, chip morphology, friction coefficient and surface quality during turning of titanium. The results showed that in both low and high concentration metal working fluid the life of cutting tool is reduced due to lack of lubrication and cooling effect, respectively; however, 10% metal working fluid concentration resulted in best machining performance. Erhan and Asadauskas [27] conducted a thin film oxidation test to determine the oxidation stabilities of vegetable oils, mineral oils and synthetic biodegradable base stocks. Soybean oil and sunflower oils were considered for the evaluation of vegetable oils. The results of oxidation tests indicated the lower oxidation and thermal stabilities of vegetable oils; however, oxidation stability of these oils was improved by the chemical modification of triglycerides.

Abdalla and Patel [28] investigated various plant-derived oils and vegetable oils in their pure state, blends and commercially available products. A set of standard techniques was used to analyze the tribological properties of the lubricants viz. pressure differential scanning calorimetry (PDSC), sliding resistance value, four-ball tester and micro-tap methods. The authors have concluded that pure state of plant oils and vegetable oil possess high level of oxidation stability. Jayadas et al. [29] evaluated the tribological behavior of coconut oil in a two-stroke engine and a four-ball tester. The experiments were conducted to evaluate the effect of extreme pressure and antiwear additive on the tribological performance of coconut oil. The coconut oil showed the lower friction coefficient and the higher wear rate compared to commercial lubricants. However, the addition of the extreme pressure and antiwear additive to coconut oil showed the reduction in friction coefficient and wear. Govindapillai et al. [30] carried out the analysis of pour point of various vegetable oils to understand their crystallization behavior using differential scanning calorimetry (DSC) method. Among the various vegetable oils, coconut oil showed the highest pour point which can be ascribed to the abundant amount of saturated fatty acids. Two different methods—addition of additives and chemical modification procedures—were carried out to modify the coconut oil pour point. The results showed a significant improvement in the coconut oil pour point using chemical modification method. Masjuki et al. [31] evaluated the diesel engine performance by applying various percentages of coconut oil blends with ordinary diesel fuel. The influence of coconut oil-blended fuel on engine wear and its lubrication properties was analyzed in terms of concentration of wear particles, oxidation, total base number, water concentration and viscosity. The 10–30% coconut oil blends showed a slightly higher performance in terms of brake power and lower exhaust emissions than those of an ordinary diesel fuel.

Thottackkad et al. [32] carried out the analysis of various concentrations of copper oxide (CuO) nanoparticles in coconut oil with the perspective of its tribological behavior in a pin-on-disk tribometer. The results indicated that at an optimum concentration of nanoparticles, the specific wear rate and the friction coefficient were the lowest. Jayadas and Prabhakaran [33] compared the oxidation stability, thermal stability and cooling behavior of sunflower oil, sesame oil, coconut oil and mineral oil. The onset temperature of decomposition method was used to determine the oxidative and thermal stabilities. An analysis of the results revealed that coconut oil has a lower onset temperature of thermal degradation than the sesame and sunflower oil, whereas for oxidative degradation vegetable oils and mineral oil showed comparable values.

Vamsikrishna et al. [34] investigated the application of nano-lubricants in turning of AISI 1040 steel with carbide tool insert. SAE-40 and coconut oil were considered as base lubricants of cutting fluids, and nano-boric acid was added to the cutting fluids. Variations of tool wear, surface quality of workpiece and cutting tool temperatures were evaluated. The coconut oil-based nano-lubricants showed a superior performance than the mineral oil-based nano-lubricants due to their enhanced lubrication properties. Attanasio et al. [35] carried out the turning tests to asses wear mechanisms of tool inserts under various machining conditions. Results of their study revealed that by applying the MQL on the tool rake face there is no significant improvement in the tool life compared to dry machining. However, when MQL is applied to the tool flank, an increased tool life was obtained. Hence, vegetable oil-based cutting lubricants have superior performance compared to other types of cutting fluids.

2 Vegetable oil-based cutting lubricants in machining process

Since from ancient times, fats and biodegradable vegetable oils are used as metal working lubricants. The use of vegetable oil-based cutting lubricants may reduce the serious health problems faced by workers such as toxic mist inhalation in the working environment, dermatological and other genetic diseases. Vegetable oil-based cutting lubricants can be used as a substitute to the synthetic fluids and the mineral oil-based cutting fluids for their less toxicity, biodegradability and renewability. The vegetable-based cutting fluids have excellent boundary lubrication properties, are hydrolytically stable and have lower filterability compared to mineral oil [13, 20]. The majority of vegetable oils contains similar structures in which polar group (–COO–) is bonded to the triglycerides. The triglyceride structure has long-chain fatty acids attached at the hydroxyl group by ester linkage. These fatty acids available in vegetable oils differ in their carbon chain length and number of double bonds. In vegetable oils, the unsaturated double bonds in the fatty acids provide many active sites for chemical reactions resulting in oxidation stability and low-temperature properties [3, 36]. The schematic representation of triglyceride structure is shown in Fig. 1. The polar group in the triglycerides has a strong tendency to interact and form a firm monolayer on metallic surfaces. A monolayer of vegetable oil molecules adsorbed on metallic surfaces and the orientation of carbon chains in perpendicular direction to the surface are depicted in Fig. 2. The higher concentration of saturated fatty acids in the vegetable oils provides a stronger protective layer on the metallic surface minimizing friction and wear due to the formation of high strength lubricating film when compared to the unsaturated fatty acids [16]. The similarity in most of the vegetable oils structure is also the basis for limiting their use as lubricants. The formulation of a vegetable oil lubricant is being developed based on the benefits and limitations of vegetable oils. However, the addition of additives can significantly increase the antiwear and friction properties of vegetable oils [36, 37]. Fully formulated vegetable oils provide the lower friction coefficient, enhanced wear resistance, boundary lubrication and hydrodynamic lubrication on metallic surfaces with strong physical and chemical adsorption properties [13]. With the increased interest in renewable and biodegradable lubricants, it is important and necessary to study their performance in machining operations.

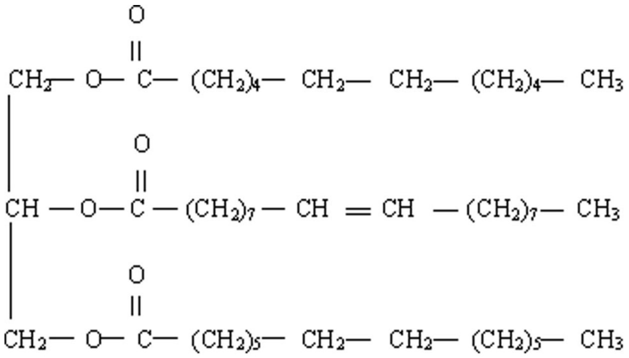


Fig. 1 Schematic representation of triglyceride structure [37]

In the present work, coconut oil has been used as the metal working lubricant due to its good oxidative and thermal stability which is higher than that of the other widely used vegetable oils in the metal-cutting industry. Most of the commercial-grade coconut oils are derived from copra, the dried meat of coconut. Among all the vegetable oils, coconut oil has abundant lauric acid and belongs to a unique group of vegetable oils called lauric oils. Coconut oil has more than 90% low molecular weight saturated fatty acid which provides a strong resistance to oxidative stability. The chemical composition of coconut oil is given in Table 1. The unsaturation value of coconut oil is determined by its iodine value which is in the range of 7–12. The other parameters such as cetane number and specific density are 37 and 0.93 g/cm^3, respectively. The flash point and viscosity index of coconut oil are 294 °C and 130, respectively. The aforementioned properties of coconut oil make it suitable for machining as coolants in conjunction with higher lubricating and cooling properties and better wettability characteristics [16, 20, 29, 33–38]. Wettability can be used to determine the wetting capability of lubricants to spread on a solid surface. The degree of

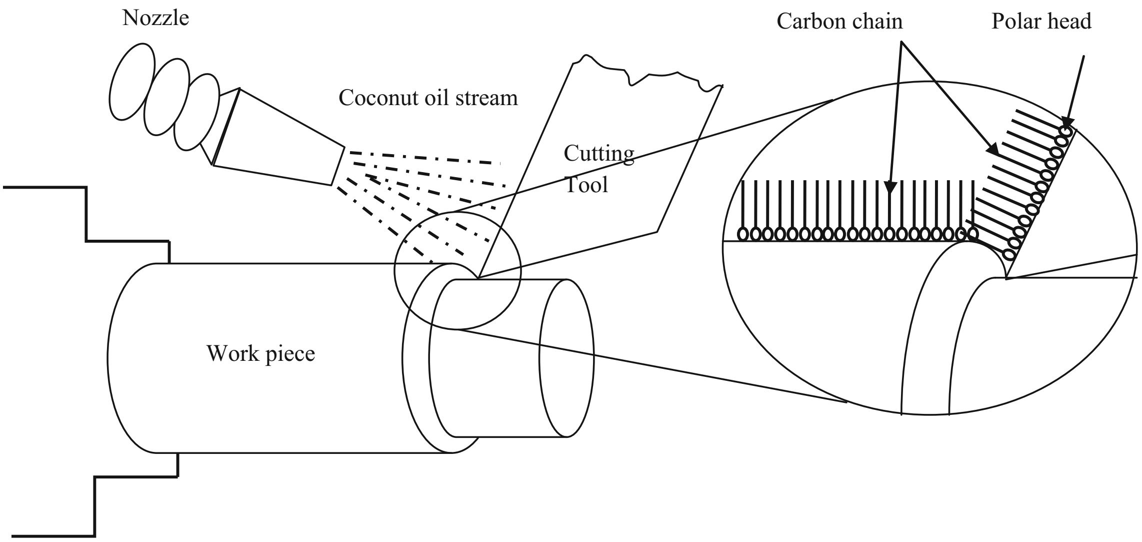


Fig. 2 Monolayer of vegetable oil molecules adsorbed on metallic surfaces

Table 1 The chemical composition of coconut oil

Component	Fraction (%)
Lauric acid (C 12:0)*	51.0
Myristic acid (C 14:0)	18.5
Caprilic acid (C 8:0)	9.5
Palmitic acid (C 16:0)	7.5
Oleic acid (C 18:1)	5.0
Capric acid (C 10:0)	4.5
Stearic acid (C 18:0)	3.0
Linoleic acid (C 18:2)	1.0

*(C XX:Y) represents a fatty acid chain, where XX indicates the number of carbon atoms and Y represents the number of double bonds

wetting is determined by wetting angles of lubricants formed at the three-phase interface, whereas the rate of wetting indicates how fast the liquid spreads on the substrate. Wettability is influenced by some parameters viz. thermal conditions of the substrate, surface texture and inherent properties of the liquid medium [19, 39]. The equilibrium thermodynamic contact angle (θ) of a liquid medium placed on the flat surface of a solid is given by Young–Dupre equation:

$$\cos\theta = \frac{\gamma_{\mathrm{sg}} - \gamma_{\mathrm{sl}}}{\gamma_{\mathrm{gl}}} \tag{1}$$

where $\gamma_{\mathrm{sg}}, \gamma_{\mathrm{sl}}$ and γ_{gl} represent the solid–gas, solid–liquid and the gas–liquid surface tensions, respectively. A schematic sketch of liquid droplet resting on an ideal solid surface is depicted in Fig. 3. However, the above equation is valid for an ideal solid surface that is chemically homogeneous, non-reactive, rigid, flat and insoluble not allowing any physical or chemical interaction between the spreading liquid and the solid surface. However, most of the real surfaces behave in a different manner based on their surface characteristics, and the apparent contact angle formed on a rough surface by a liquid is given by Wenzel equation.

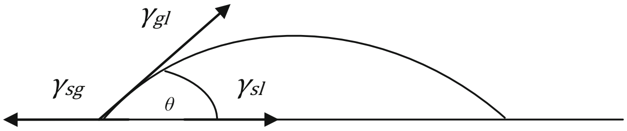


Fig. 3 A sketch showing contact angle at the solid–liquid interface

$$\cos\theta_{\mathrm{W}} = r\cos\theta \tag{2}$$

where θ_{W} is the apparent contact angle obtained on a rough surface and r is the average roughness factor, which represents the factor by which roughness increases the contact area. For ideal surfaces, the value of r is equal to unity, and for real surfaces, r is always greater than unity [40–42]. The lubricant having a higher surface tension rests on a low surface energy substrate resulting in a high contact angle and a spherical shape. On the other hand, the substrate surface energy exceeds the lubricant surface tension resulting in a low contact angle which results in good wettability characteristics. For practical purposes, if the lubricant is said to wet the solid substrate, the value of the wetting angle is less than 90°, whereas the lubricant does not wet the solid substrate if the value of the wetting angle is greater than 90° [43, 44].

There is a close relation between the wetting characteristics of lubricants and heat transfer. A number of industrial applications viz. brazing, printing, lubrication, spray quenching, adhesion, coating, soldering essentially involve spreading and wetting processes. The rate of heat removal from a heated component depends on the cooling properties of the lubricants. The conventional and non-renewable mineral oil-based lubricants are usually used for industrial heat treatment which causes several environmental issues such as soil contamination, air and water pollution. The use of biodegradable vegetable oils in industrial heat treatment has many advantages due to their environmental friendliness [39, 45]. Vegetable oil molecules are long, heavy and dipolar in nature, which gives them a greater capacity to form a strong lubricating film on metallic surfaces.

3 The effect of tool wear pattern and chip morphology on machining performance

In machining processes, tool wear is considered as one of the most significant factors to evaluate productivity and manufacturing efficiency. Tool wear in cutting process occurs due to high cutting temperatures and relative higher speeds between chip-tool and work-tool interfaces leading to the formation of severe tribological contacts between the cutting tool and the workpiece. Under high-speed machining operating conditions, the intimate contacts are often very much difficult to lubricate and subsequently the cutting tool losses its function [46]. In general, under various machining conditions, carbide cutting tool inserts consisting of high toughness, strength and hot hardness may fail due to gradual wear [5]. Wear damage on cutting tool inserts has been divided into distinct wear features. The crater wear on the tool rake face, and the flank and notch wear on the flank clearance face are depicted in Fig. 4. The crater wear is mainly caused by the intimate contact between the chip and the tool rake face, expressed by measuring the crater depth $K_{\max}$. The flank wear on the cutting tool is caused due to the abrasive contact between the cutting tool and the freshly cut workpiece. Further, flank wear is divided into an average width of flank wear (V_B) and a maximum width of flank wear (V_M). Notch wear (V_N) is caused by fracture that occurs on brittle tools during machining of hard materials. Among the above-mentioned wear patterns, flank wear is one of the most dominating wear patterns responsible for the increase in the cutting forces and the related problems [47, 48]. ISO has recommended the maximum flank wear width of 0.3 mm and 0.6 mm for finishing and roughing operations, respectively [49].

The various types of wear mechanism such as adhesion, abrasion, diffusion and oxidation may appear on the tungsten carbide (WC) cutting tools during machining of steel materials. Therefore, it is essential and necessary to have knowledge about the tool wear mechanisms which helps in predicting the cutting tool life during metal-cutting operation. Adhesive wear occurs due to the formation and subsequent breakage of welded asperity junctions between the workpiece and the cutting tool. The abrasive wear occurs due to the hard phase particles or inclusions present in the workpiece which results in removal of the cutting tool material by scoring action. Diffusion wear takes place due to difference in the concentration of atoms; as a result, atoms from the cutting tool material diffuse into the workpiece and the rate of diffusion increases exponentially with the increase in temperature. Hence, under a given set of machining conditions, it is relatively difficult to determine the dominant wear mechanism. According to the temperature distribution on the face of the cutting tool, the main causes for crater wear are abrasive wear, adhesive wear and diffusion wear. The flank wear occurs due to the abrasive action of hard phase particles present in the

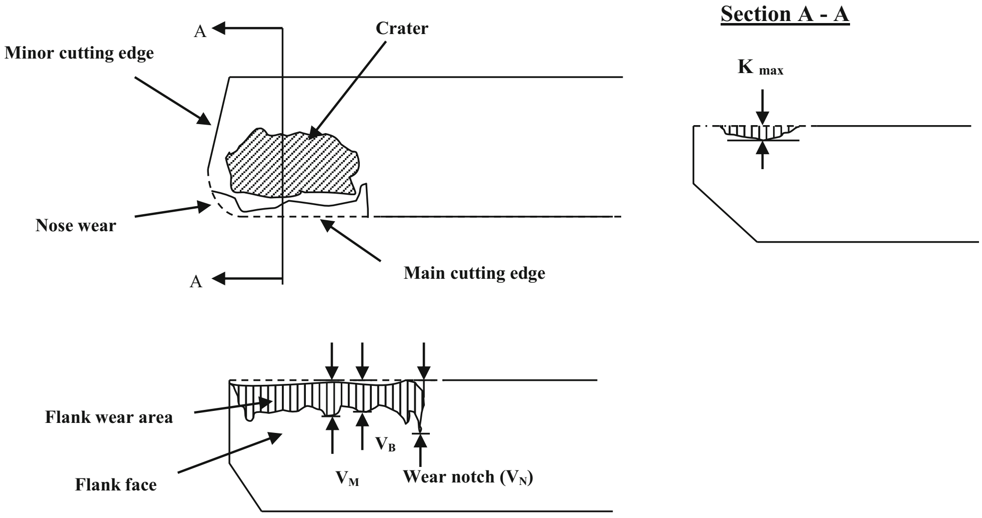


Fig. 4 Illustration of tool wear according to ISO 3685 [49]

workpiece material [50, 51]. Chips produced during machining directly influence the machining behavior viz. cutting temperature, tool wear and surface finish [53]. In the literature, the correlation between the cutting forces and the tool wear with respect to various cooling techniques is fairly investigated during machining of steels. However, the correlation between mechanism of chip formation under different cooling strategies has not been adequately established [54]. The influence of the machining environments on the properties of workpiece material and the corresponding changes in the chip segmentation mechanism have been investigated and discussed in this work. The review of the literature highlights the potential use of vegetable oils to enhance the performance of cutting tools.

The main objective of the present experimental work is to investigate the role of minimum quantity lubrication (MQL) by coconut oil on tool wear, friction coefficient, surface roughness and chip morphology in turning operation performed on AISI 1040 steel. A wettability study on the cutting fluids was conducted to measure angle of contact of coconut oil, mineral-based oil on the tool material to justify the unique properties of coconut oil which enhanced the machining performance. Further, a comparison on the tool performance is also made to analyze cutting effectiveness of MQL using coconut oil with that of dry, wet, coconut oil and MQL using soluble oil conditions.

4 Experimental setup and procedure

In this study, all the turning experiments were conducted on a 20-kW spindle power HMT center lathe. A workpiece of AISI 1040 steel with hardness 30 ± 2 HRC, length 400 mm and diameter 57 mm was used to perform the experiments. The experiment details are given in Table 2. The commercially available tungsten carbide tool inserts, the most extensively used in machining operation, were used to carry out turning experiments. The experiments were carried out in five different machining environments viz., dry, wet, coconut oil, MQL with soluble oil and MQL with coconut oil. A fresh tungsten carbide cutting tool insert was used for each experiment. The friction coefficient, cutting force, tool wear, surface roughness and chip morphology are considered to assess the machinability characteristics of workpiece material. The photographic view of experimental setup is depicted in Fig. 5. For all cutting conditions, the machining parameters such as cutting speed, feed rate and depth of cut were kept constant. The average cutting force values were calculated from a three-component piezo-electric dynamometer (KISTLER-type 9257A). The KISTLER-type 5233A charge amplifier was used to convert the generated charge into voltage, and via a Kistler Dynoware software force data were fed into a personal computer. A digital USB microscope was used to monitor the crater, flank and auxiliary wear on the tool

Table 2 Experimental details

Work specimen	
Material	AISI 1040 (C = 0.36–0.45%, Mn = 0.6–1%, Si = 0.2–0.3, %, S = 0.025%, P = 0.015%),
Size	ø57 mm × 400 mm
Hardness	30 ± 2 HRC
Process parameters	
Cutting velocity	$V = 114$ m/min
Feed	$S = 0.10$ mm/rev
Depth of cut	$t = 0.5$ mm
Environment	Dry, wet, MQL by soluble oil, coconut oil, MQL by coconut oil
Flow rate of lubricant	
Wet (flood cooling)	200 ml/min
MQL by soluble and MQL by coconut oil	60 ml/h
Coconut oil	10 ml/min
Machine tool	
Lathe machine	HMT Company, India
Motor capacity	20 kW
Spindle speed	59–2100 rpm
Cutting tool	DCMT11T304, carbide insert
Tool holder	SDJCR 2020 K11 WIDAX
USB optical microscope	2 M pixels

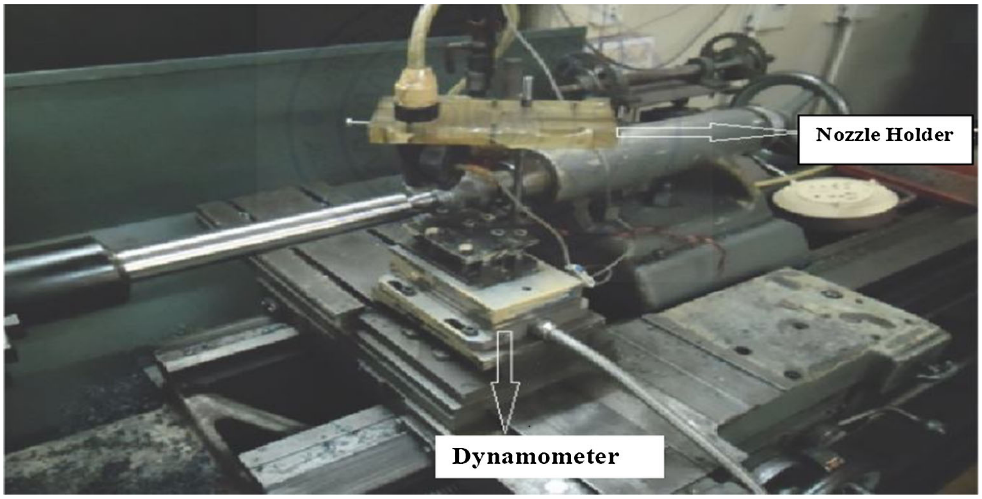


Fig. 5 Photographic view of experimental setup

insert. The Qualitest TR 100 perthometer was used for surface roughness (R_a) measurements at various points on the machined surface, and the average surface roughness values were considered to assess the surface quality.

The worn cutting tools were analyzed using a scanning electron microscope (SEM) to examine the development of wear mechanisms. A photographic view of the experimental setup is shown in Fig. 6. After each cut, we measured (1) surface roughness using perthometer, (2) dimensional accuracy on the workpiece using digital vernier caliper, (3) flank and auxiliary wear on the cutting tool insert and observed (4) the chip morphology using SEM.

4.1 Contact angle measurement using goniometer

The macroscopic contact angles of sessile droplets of coconut oil and conventional cutting lubricants on tungsten carbide (WC) tool material were measured with a high-performance image processing goniometer (Data Physics OCA 15EC). A droplet volume of 10 µl was considered for contact angle measurement, and a micro-metering syringe was used to measure the size of droplets. The sample surfaces were cleaned by ethanol and dried after every measurement. The droplet image was then transferred to the computer, via an image process software that calculates the contact angle. These properties were characterized by static contact angle measurements at room temperature in a sessile drop arrangement.

4.2 Working principle of MQL delivery system

The schematic diagram of the minimum quantity lubrication (MQL) setup is shown in Fig. 6. MQL, also called near-dry machining (NDM), utilizes small quantities of cutting lubricants in the range 50–500 ml/min to carry out machining processes. In a given set of parameters, MQL technique offers substantially better performance in removing heat from the cutting zone than the flood cooling. Further, MQL also minimizes the costs of filtration and recycling of cutting lubricants [6, 9]. The MQL method involves mixing of the drops of cutting fluid with pressurized air generating a spray which is then directed to the cutting zone, thereby greatly reducing the quantity of cutting lubricant to be used in machining processes. In the present system, high-pressure air was set at 7 bar and the pressure control valve was used to regulate the air pressure. The pressurized air from the compressor and the cutting fluid from the fluid chamber were mixed in the mixing chamber. At a very high velocity, the resulting spray was impinged on the chip-tool and work-tool contact area through the nozzle. The pressurized air along with the metal working lubricant reaching the cutting surface performs both cooling and lubrication action, respectively. The application of MQL technique can reduce the temperatures generated at the rake face, the flank face and protect the auxiliary flank face resulting in a better dimensional accuracy.

5 Results and discussion

5.1 Wettability study

Figure 7 shows the captured contact angles of droplets of pure water, conventional cutting lubricant and coconut oil as they spread on tungsten carbide tool insert. It is observed that the spreading behavior of coconut oil is significantly better than that of conventional cutting lubricants and pure water. The equal quantity of the droplet volume of 10 µl

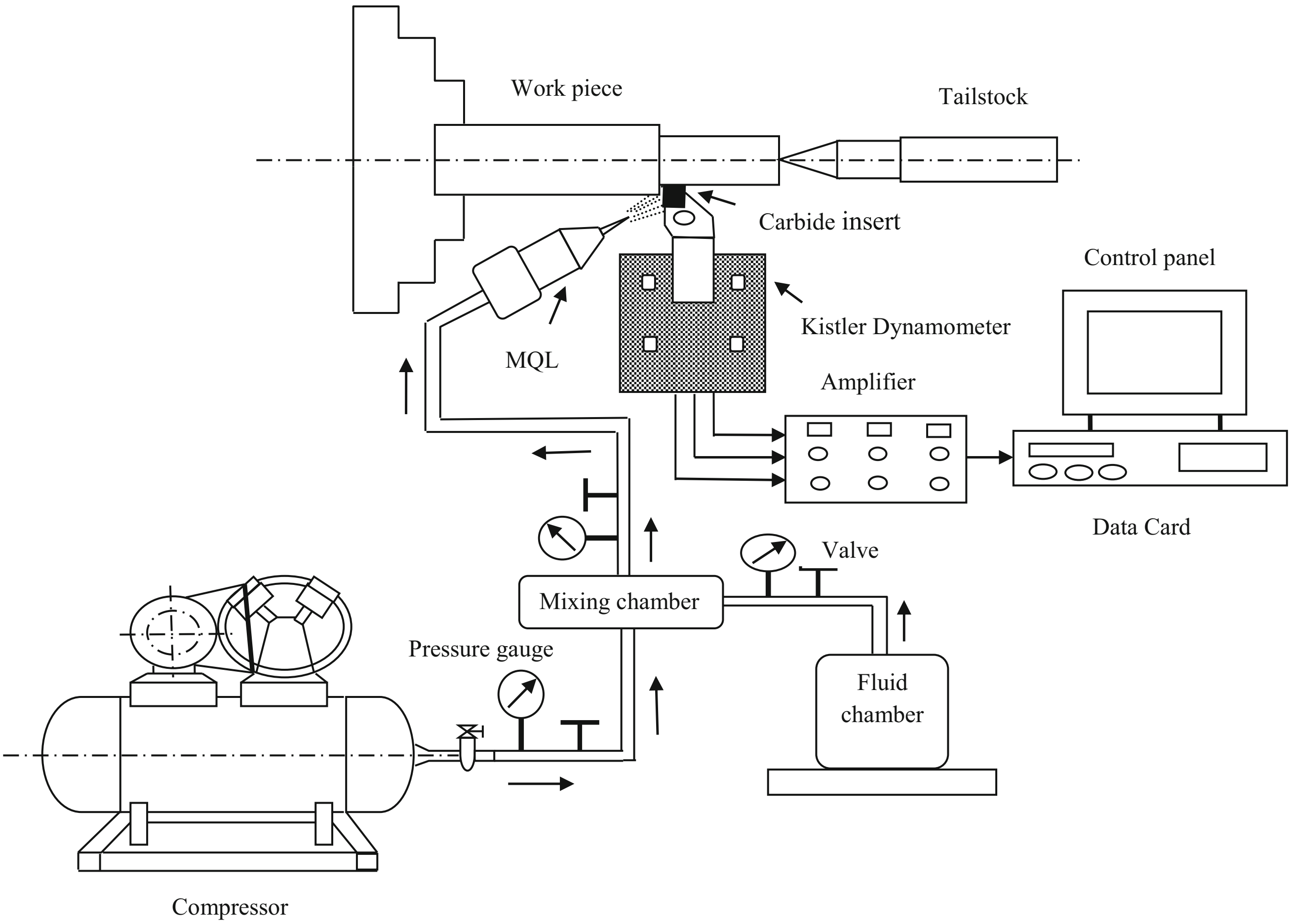


Fig. 6 Schematic diagram of experimental setup

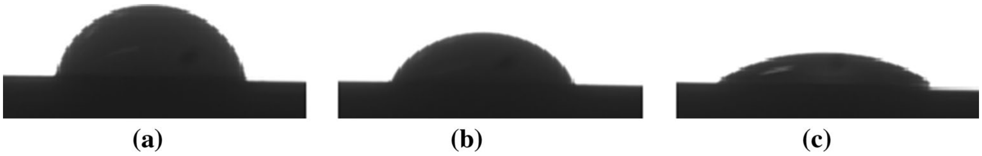


Fig. 7 Images of droplets of **a** pure water ($\theta = 75.4°$), **b** soluble oil ($\theta = 68.1°$) and **c** coconut oil on tungsten carbide tool substrate ($\theta = 33.7°$)

was ensured by a micro-metering syringe, and all the measurements were taken at room temperature. The obtained data clearly indicate that the coconut oil affects the adhesive and cohesive force interfaces at the contact line. Further, in the case of coconut oil, the wetting area per unit volume of the droplet gradually increases, thereby enhancing the lubricating and heat removal properties.

5.2 Tool wear assessment

The life of cutting tools is considered an important economic factor due to its significant role in increasing productivity. During machining, excessive heat is produced along the three deformation zones—primary, secondary and tertiary shear zone. The three heat sources increase the temperature at the chip-tool contact area which leads to premature cutting tool failure, thereby causing dimensional deviation of the workpiece [1, 5]. Generally, the wear on cutting tools takes place in three stages. In the first stage at the beginning of machining, the cutting tools normally undergo rapid break in wear. Further in the second stage, a slow mechanical wear on the cutting tool can be observed followed by a faster wear rate in the third stage at the end of the machining process [6]. Several types of wear mechanisms such as adhesion, abrasion, attrition, diffusion, chipping, fracture, flaking and plastic deformation influence the cutting tool life, and therefore it is essential and necessary to have knowledge about them.

Tool wear is divided into crater wear on the tool rake face and flank wear on the flank surfaces. The crater wear on the tool rake face occurs due to the continuous interaction between the chips and the tool surface, and it is formed at some distance away from the cutting edge where the cutting temperature is maximum. The flank wear on the clearance surfaces occurs due to the rubbing of cutting tool with the workpiece where the abrasion wear is the dominant wear mechanism [7–9]. However, the crater wear on the tool rake face occurs due to the chemical interactions between the chip and the tool. In order to enhance the life of the cutting tools, conventional cutting lubricants are applied to cool and lubricate the machining process. Moreover, the use of conventional cutting lubricants creates several adverse effects on environment. Therefore, to minimize these effects the substitutes to conventional cutting lubricants have been suggested such as solid lubricants, high-pressure coolants, air-gas-vapor coolant, cryogenic cooling, vegetable-based oils and minimum quantity lubrication [11–13, 21]. Figure 8 shows the progression of flank wear with machining time under different machining environments such as dry, wet, coconut oil, MQL using soluble oil and MQL using coconut oil conditions while turning AISI 1040 steel by tungsten carbide tool inserts at the prescribed cutting velocity and feed rate. The flank wear values obtained under coconut oil, MQL using soluble oil and MQL using coconut oil as lubricants are lower than those obtained under dry and wet machining conditions. The application of MQL using soluble oil on the tool and workpiece interface resulted in a substantial change in the chip morphology, decrease in the cutting forces and an effective control of the temperature at the cutting zone, thereby improving the tool life. The reason behind the reduction in flank wear can be ascribed to the decrease in the flank temperature under MQL environment due to which abrasion wear is minimized, thereby retaining tool hardness. The reduced flank wear is observed in the coconut oil machining condition which can be mainly attributed to its superior lubricity and unique characteristics such as oxidation stability, thermal stability, high viscosity index, high pour point. Further, when a high-pressure jet of coconut oil is applied at the chip-tool contact zone, the flank wear decreases.

On the other hand, a decrease in flank temperature resulted in a reduction in adhesion, abrasion and diffusion types of wear mechanisms. Figure 8 shows paradoxical effect of wet machining environment on the growth of flank wear compared to dry cutting condition. This flank wear growth has occurred due to the ineffective penetration of cutting fluid at the chip-tool and work-tool contact area because of which the coolant fails to remove heat effectively. The auxiliary flank wear is another essential tool wear criterion that plays a major role in machining by governing the surface finish as well as the dimensional accuracy on the workpiece. The variation of auxiliary flank wear on clearance face with respect to machining time under dry, wet, coconut oil, MQL using soluble oil and MQL using coconut oil is depicted in Fig. 9. The lesser values of auxiliary wear were obtained for coconut oil, MQL using soluble oil and MQL using coconut oil lubrication conditions as seen in the figure. The tool wear and tool life are influenced by cutting environments and application of coolants. Further, to correlate the lubrication environments on the tool wear, the SEM images of the worn-out inserts obtained during turning operation under dry, wet, coconut oil, MQL using soluble oil and MQL using coconut oil machining conditions were considered as shown in Figs. 10, 11, 12, 13 and 14, respectively. The figures show the nose, flank and auxiliary sides of the tool inserts where the maximum tool wears occurred. Figure 10a–f shows the typical SEM images of crater wear, flank wear and auxiliary wear of worn-out carbide cutting tool under dry machining. Under dry machining, even at moderate cutting velocities the temperature at the cutting zone can reach up to 900 °C. At such extreme temperature, the chip maintains a very close contact with the rake face and flank surfaces of tool, thereby causing transfer of tool

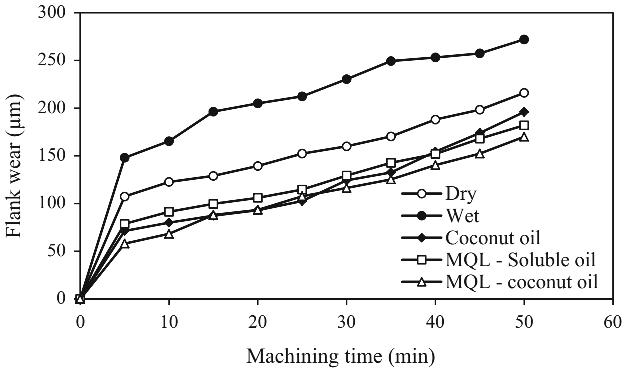


Fig. 8 Growth of flank wear with machining time

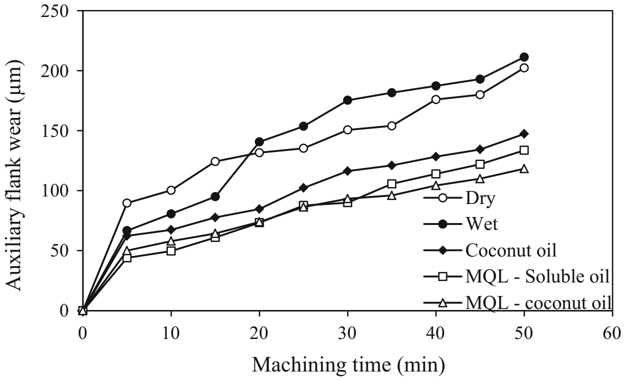
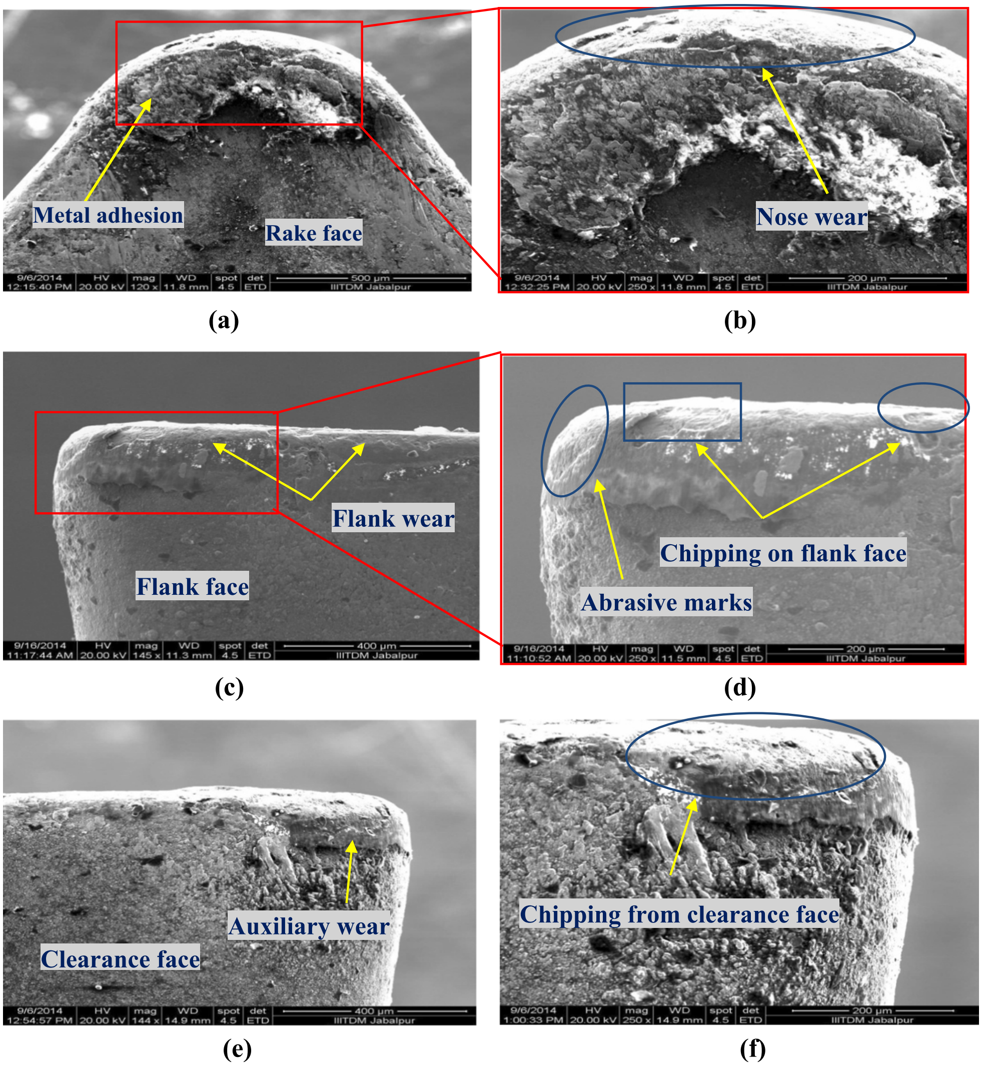


Fig. 9 Growth of auxiliary flank wear with machining time



(a) (b)

(c) (d)

(e) (f)

Fig. 10 SEM views of worn-out insert under dry cutting condition **a** crater wear, **b** close-up view of crater wear, **c** flank wear, **d** close-up view of flank wear, **e** auxiliary wear, **f** close-up view of auxiliary wear

material into the flowing chip through adhesion and diffusion mechanisms.

The examination of the crater revealed the adherent deposition of chip material on the cutting tool rake face, indicating the intimate adhesion between the tool rake face and the chip as shown in Fig. 10a. The brittleness of the cutting tool material coupled with the high stress and cutting temperature at the cutting edge may propagate the fracture and chipping of the insert. Chipping was detected at the tool nose and the cutting edge. Due to high temperatures created in the cutting zone, the cutting tool loses its strength causing plastic deformation on the tool nose region as shown in Fig. 10b. Further, abrasion marks were found on the cutting tool flank face, which are parallel to the direction of metal flow indicating the wearing of the coating layers. Abrasion is caused due to friction between the hard inclusions present in the workpiece material and the cutting tool which ultimately led to the removal of the coating as seen in Fig. 10d. Higher stresses and temperature also caused the chipping on the auxiliary cutting edge as shown in Fig. 10f. Figure 11a–f depicts the SEM micrographs of worn-out insert used under wet cutting condition. The turning operation carried out using cutting fluids did not enhance the tool life as compared to dry machining condition. The cooling rate of the cutting fluids could not cope up with the rapid heat generation at the intimate contact area. The bulk plastic contact between the chip and the tool rake face may have prevented the coolant to reach the intimate contact zone during the machining process. The examination of the tool rake surface shown in Fig. 11b depicts deep scratches that occurred due to back side of the chip flow on the tool rake surface. A significant amount of workpiece material is adhered to the rake, flank and auxiliary surfaces. Adhesion levels of workpiece

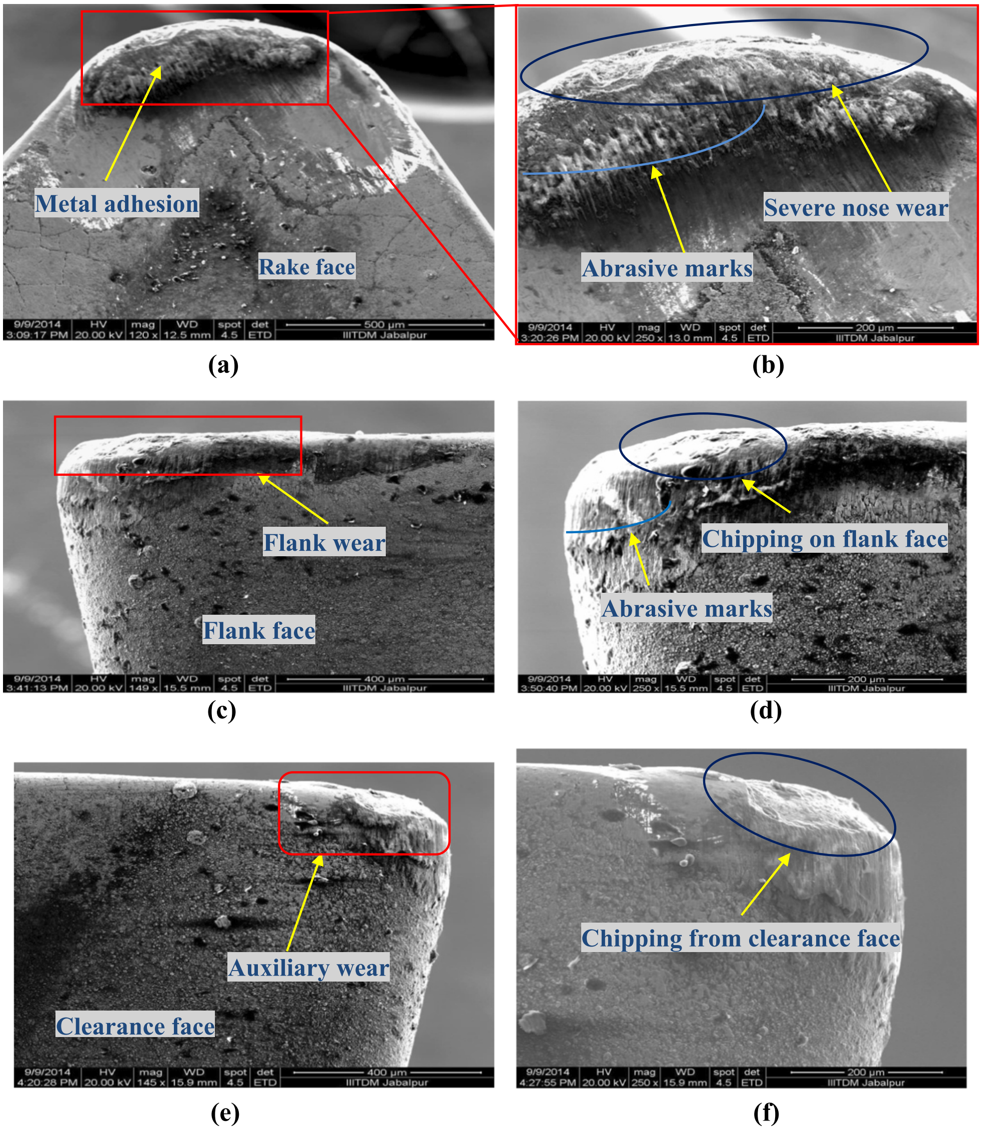


Fig. 11 SEM views of worn-out insert under wet cutting condition **a** crater wear, **b** close-up view of crater wear, **c** flank wear, **d** close-up view of flank wear, **e** auxiliary wear, **f** close-up view of auxiliary wear

material on the tool rake face were reduced during wet cutting condition. The flank face close to the nose area suffers from severe wear rate due to higher stresses and cutting temperature generated near the nose region, which resulted in a decrease in the yield strength of the tool material. Flank wear is associated with the abrasion wear tracks and adhesion of workpiece material on the flank face as shown in Fig. 11d. Further chipping was observed on the rake face, flank face and auxiliary face of the tool. The high stress and temperature are the major contributors to flaking and chipping, which caused the tool material to weld on to the rake, flank and auxiliary surfaces.

Figure 12a–f shows the SEM images of worn-out tungsten carbide tool used under MQL by soluble oil cutting condition. From the figures, it can be clearly seen that the tool wear on rake, flank and auxiliary faces reduced gradually by the application of MQL using soluble oil. Figure 12a shows the rake face of the cutting tool insert with little adhesion of the workpiece material and no signs of micro chipping, plastic deformation, flaking and fracture of the cutting edge. MQL using soluble oil machining condition resulted in a comparatively minimum and uniform flank wear and auxiliary wear on the flank and auxiliary flank faces as shown in Fig. 12d, f. The SEM views of worn-out insert under coconut oil cutting condition are depicted in Fig. 13a–f. In coconut oil machining environment, minimum tool wear is observed when compared to dry, wet, MQL by soluble oil conditions. The application of coconut oil results in the moderate adhesion on the rake, flank and clearance faces as shown in Fig. 13b, d and f,

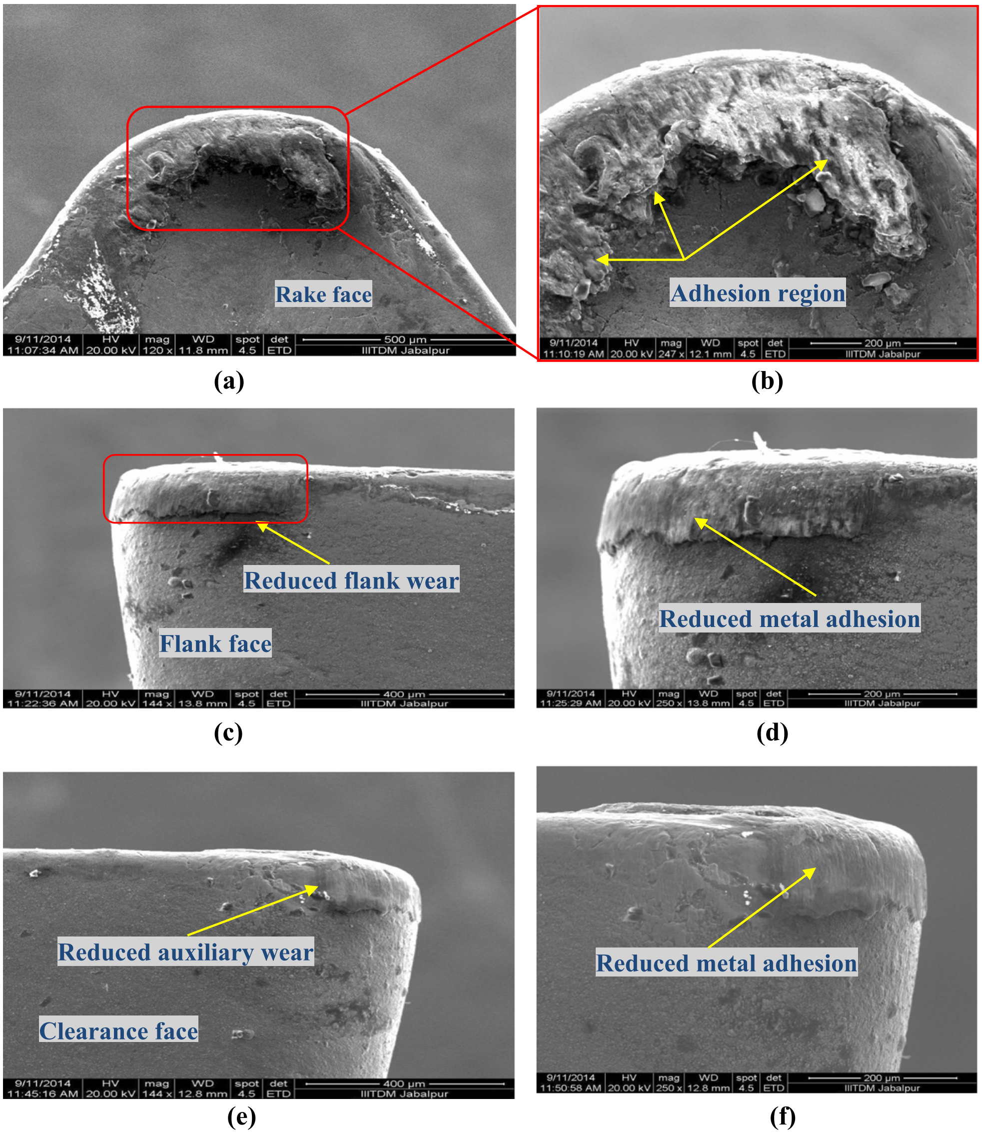


Fig. 12 SEM views of worn-out insert under MQL by soluble oil cutting condition **a** crater wear, **b** close-up view of crater wear, **c** flank wear, **d** close-up view of flank wear, **e** auxiliary wear, **f** close-up view of auxiliary wear

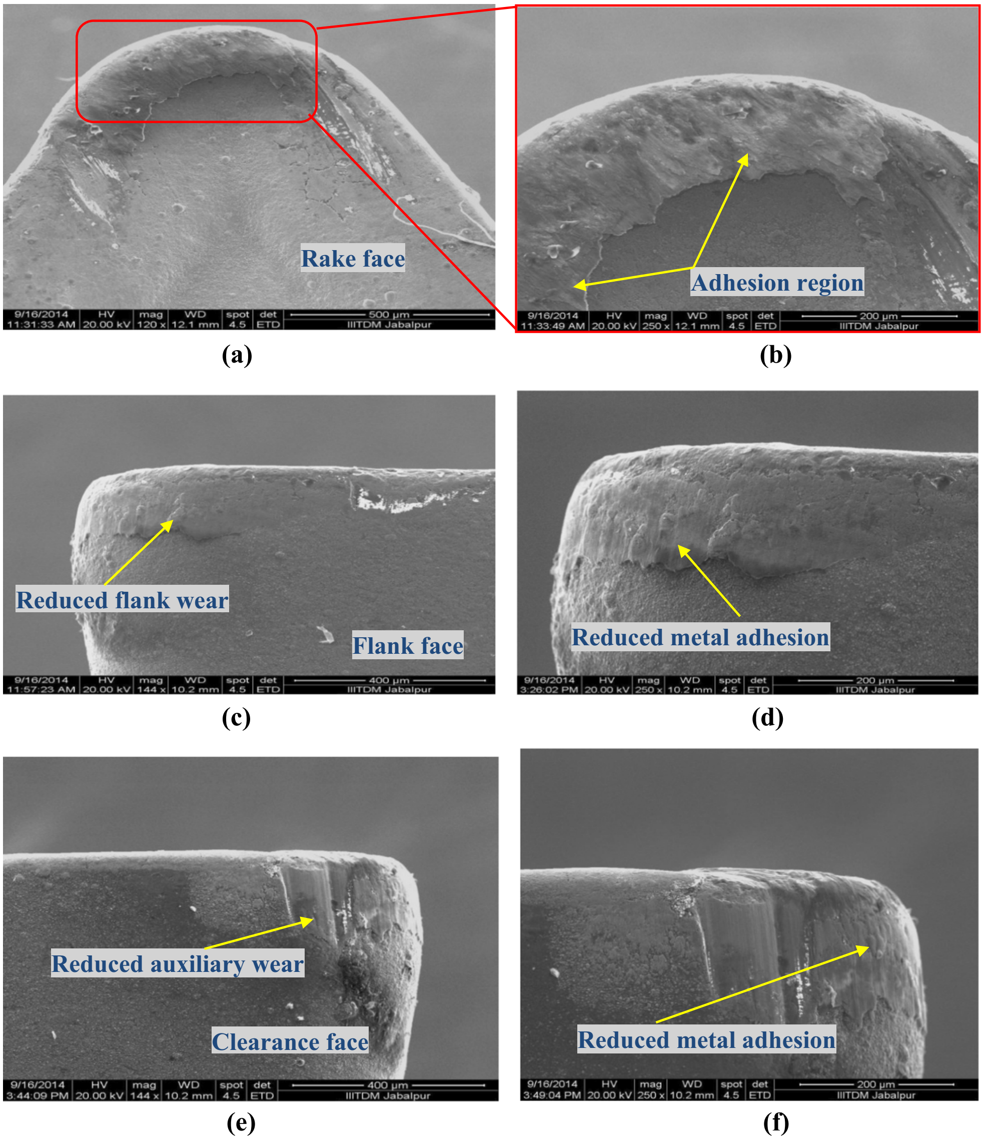
respectively. Moreover, coconut oil has higher lubricity which enabled the reduction in friction and wear at the tool and workpiece interface. On the main and the auxiliary cutting edge, the growth of groove wear significantly reduces due to the effective temperature control by coconut oil as depicted in Fig. 13d, f.

Figure 14a–f indicates the SEM images of worn-out insert used for turning operation under MQL by coconut oil. The workpiece material adhesion on the tool rake face and on the cutting edge was observed. Under all machining environments, the lubricant and the method of its application play a vital role in quantifying the volume of material adhesion. The examination of tool rake face, flank face and auxiliary face indicated a considerable reduction in wear and least adhesion of workpiece material, as shown in Fig. 14b, d, f, respectively. MQL using coconut oil easily forms a lubrication layer between the tool rake face and the chip. This happens due to high-velocity application of coconut oil through the nozzle causing reduction in the friction between the chip and tool and thereby alleviating tool wear effectively.

5.3 Friction coefficient

The average coefficient of friction at the chip-tool contact zone can be calculated using Eq. (3) [25].

$$\mu = \tan(\beta) = \tan\left[\gamma_0 + \arctan\left(\frac{F_y}{F_Z}\right)\right] \tag{3}$$



(a) (b) (c) (d) (e) (f)

Fig. 13 SEM views of worn-out insert under coconut oil cutting condition **a** crater wear, **b** close-up view of crater wear, **c** flank wear, **d** close-up view of flank wear, **e** auxiliary wear, **f** close-up view of auxiliary wear

where β is the friction angle, γ_0 is the rake angle, and F_y and F_Z are the radial cutting force and main cutting forces, respectively.

The variation of average coefficient of friction at the chip-tool contact zone with respect to the increase in cutting time while turning AISI 1040 steel under dry, wet, coconut oil, MQL using soluble oil and MQL using coconut oil machining environments is depicted in Fig. 15. The results illustrated that the application of coconut oil, MQL using soluble oil and MQL using coconut oil as lubricants greatly reduced the cutting temperature and the friction coefficient at the chip-tool interface compared to that of dry and wet machining environments. In the dry and wet machining environments, the friction coefficient values were fairly close to each other and varied in a relatively wider range of 0.62–0.68 and 0.61–0.7, respectively. This is mainly due to the increase in contact stress which creates more bonding at the seizure zone and leads to a greater possibility of chip-tool micro-welding in the sliding zone increasing the cutting load on the tool rake face, thereby resulting in higher friction and tool wear which are evident from Figs. 10b and 11b.

The coefficient of friction is least for MQL using coconut oil machining environment followed by coconut oil and MQL using soluble oil, respectively. In the above-mentioned machining environments, the coefficient of friction has been greatly reduced due to the formation of thin lubricating film between the chip-tool contact zone that prevents strong adhesion between the tool rake face

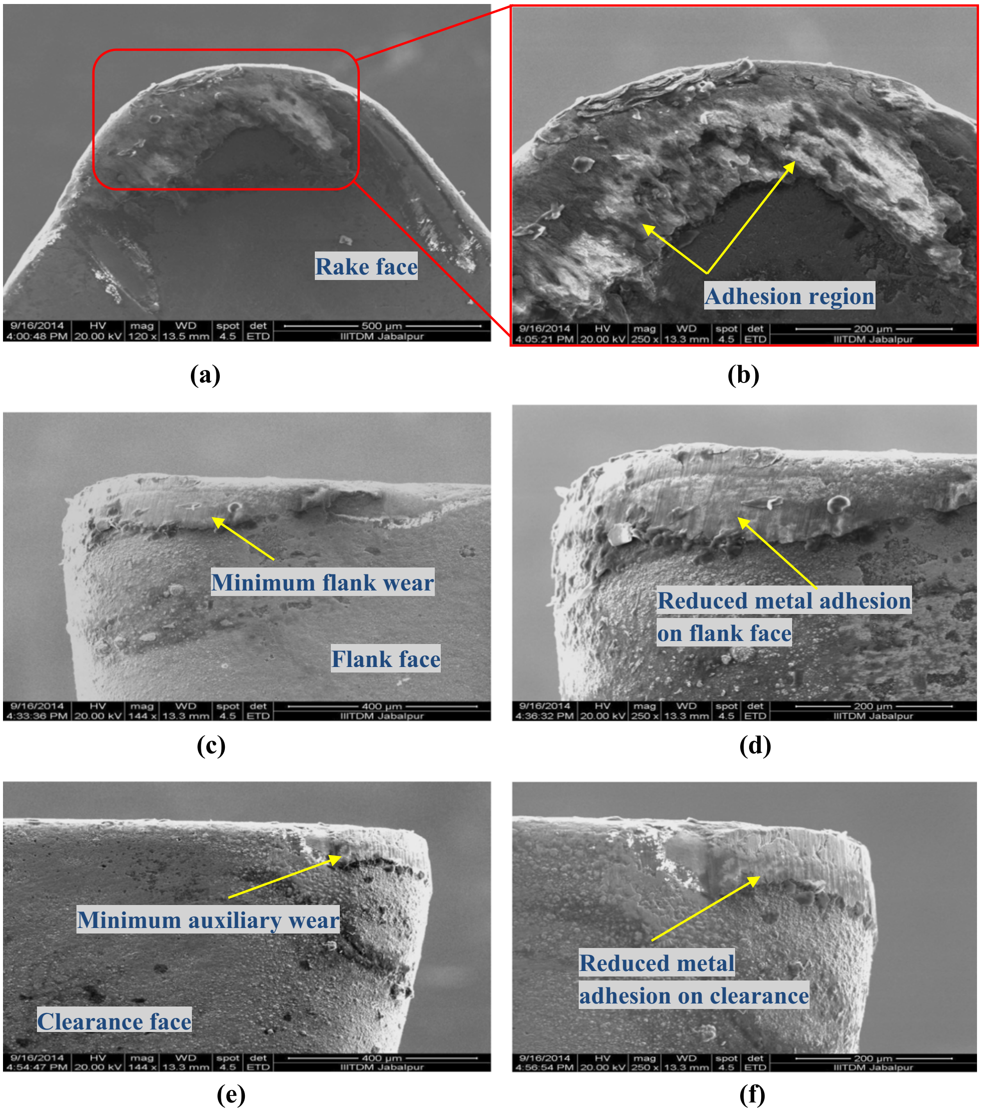


Fig. 14 SEM views of worn-out insert under MQL by coconut oil cutting condition **a** crater wear, **b** close-up view of crater wear, **c** flank wear, **d** close-up view of flank wear, **e** auxiliary wear, **f** close-up view of auxiliary wear

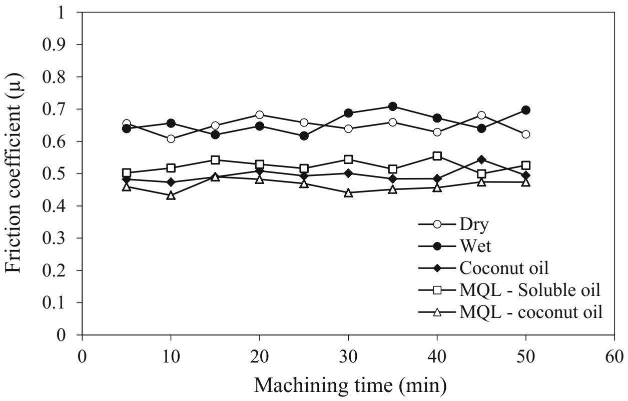


Fig. 15 Friction coefficient, μ with machining time

and the chip as evident from Figs. 12b, 13b and 14b, respectively. Hence, the friction mechanism in the secondary deformation zone of the chip dominated by shearing and galling was changed to pure sliding.

5.4 Surface roughness

Surface roughness is the important index of machinability, influencing the performance and service life of the machined products as well as the production cost. In addition, surface roughness has significant effects on the surface sensitive properties such as creep strength, fatigue behavior, corrosion resistance. The roughness of the machined products is greatly influenced by the machining conditions viz. feed rate, cutting velocity and depth of cut.

The poor surface finish of the product manufactured by turning operation is a result of the regular feed marks left by the cutting tool tip on the finished surface, the irregular deformation of the auxiliary cutting edge at the tool tip, chipping, fracture, built-up edge formation, tool wear, vibration in machining system, etc. Hence, it is necessary to know the cutting parameters, which reduces the tool wear and generate favorable surface characteristics [6, 52]. The variation of surface roughness while turning AISI 1040 steel by tungsten carbide cutting tool insert at a prescribed set of feed rate, cutting velocity and depth of cut under dry, wet, coconut oil, MQL using soluble oil and MQL using coconut oil as lubrication conditions is depicted in Fig. 16.

The surface roughness increased substantially with the increase in cutting time under different tool-work environment combinations. Among the aforementioned environments, surface roughness values were drastically reduced by the application of MQL using coconut oil followed by MQL using soluble oil and coconut oil, respectively. The decrease in surface roughness can mainly be ascribed to its greater cooling and lubrication effect which results in chip up curling and better lubricant penetration into the cutting zone shortening the chip-tool contact length. The reduction in frictional forces and temperature developed between the tool and the work interface minimizes chipping, abrasion and built-up edge formation, thus resulting in minimum deterioration to the auxiliary cutting edge as evident in Figs. 12f, 13f and 14f. Figures 10f and 11f clearly show severe deterioration on the auxiliary cutting edge due to sever chipping and abrasion which is directly reflected on the finished surface obtained by the dry and wet machining environments.

5.5 Chip morphology

A morphological analysis of chips was carried out to analyze the influence of machining environments on the chip formation mechanism. For each chip sample, two SEM images were acquired to examine the morphology of the free and back surfaces of the chip. Figures 17, 18, 19, 20 and 21 depict the chip morphological images obtained under various cutting environments. A chip consists of two surfaces: the free surface and the back surface. The free surface consists of serrated rough aspect caused due to shear mechanism, whereas the back surface maintains the close contact with the tool rake face. When the chip slides up the tool rake face during the cutting process, a high contact pressure and frictional forces are created on its back surface generating high cutting temperature, thereby resulting in a flat and bright back surface. Further, a fracture appears on the chip when the shear stress reaches the limit of material strength [53, 55].

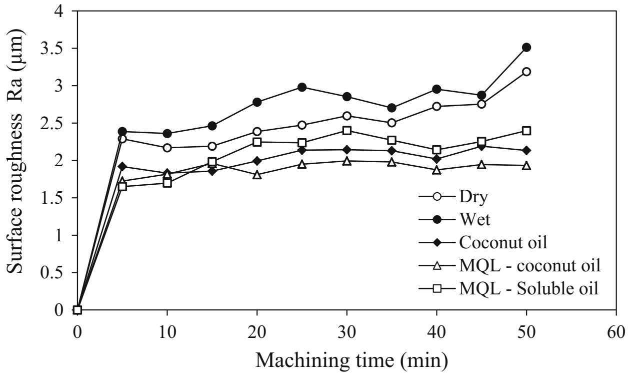
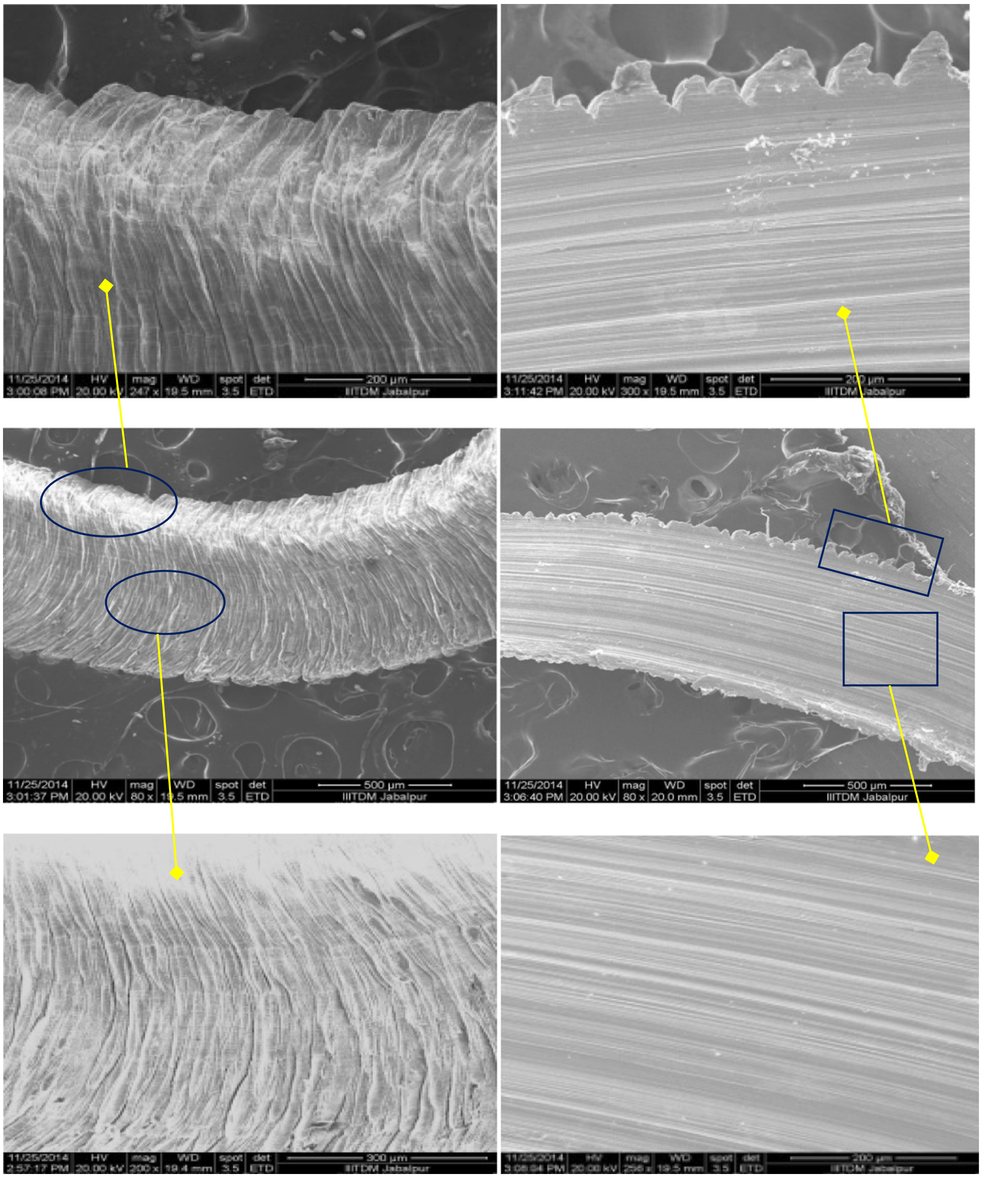


Fig. 16 Surface roughness values, Ra with machining time

During dry machining, longer and curling chips are produced. In such cases, an increase in chip-tool contact length results in higher friction coefficient values between the chip and the tool. Further, these chips get curled within the tool-workpiece interface and need to be removed at short time intervals during machining [54, 56]. In dry machining, the high temperature in the shear zone causes thermal softening of work and tool material. Under this condition, the top surface of tool rake face and the chip sliding on it are welded together which causes the transfer of thermally softened layer on the tool rake face into the sliding chips, resulting in higher chip thickness in dry machining process [57]. The chip morphology of dry machining environment is shown in Fig. 17a, b. Figure 17a shows the free surface side of the chip along with the magnified images. From the magnified images, a loose and lamella structure can be seen caused by the shear mechanism and the lamellas pattern appears deeper indicating higher temperature in the shear zone. On the other hand, Fig. 17b depicts the underside of the chip along with its magnified images. The friction is much more severe at the chip-tool contact area. This is because the chip maintains a very high close contact with the tool rake face, which increases the friction and the corresponding temperature. As a result, the abrasive scratch marks appear on the back side of the chip. The sharper edges of the chips are formed during machining of AISI 1040 steel under dry machining environment due to localization of heat in the shear zone but are significantly reduced during machining under wet, coconut oil, MQL using soluble oil and MQL using coconut oil. The chip morphology of wet machining environment is shown in Fig. 18a, b. The free surface side of the chip along with the magnified images is shown in Fig. 18a. A close-up view of the magnified images shows lamellas structure on the free surface with much deeper patterns than that obtained under dry machining. When the machining is carried out with conventional cutting lubricants, a hydrodynamic layer is formed between the tool

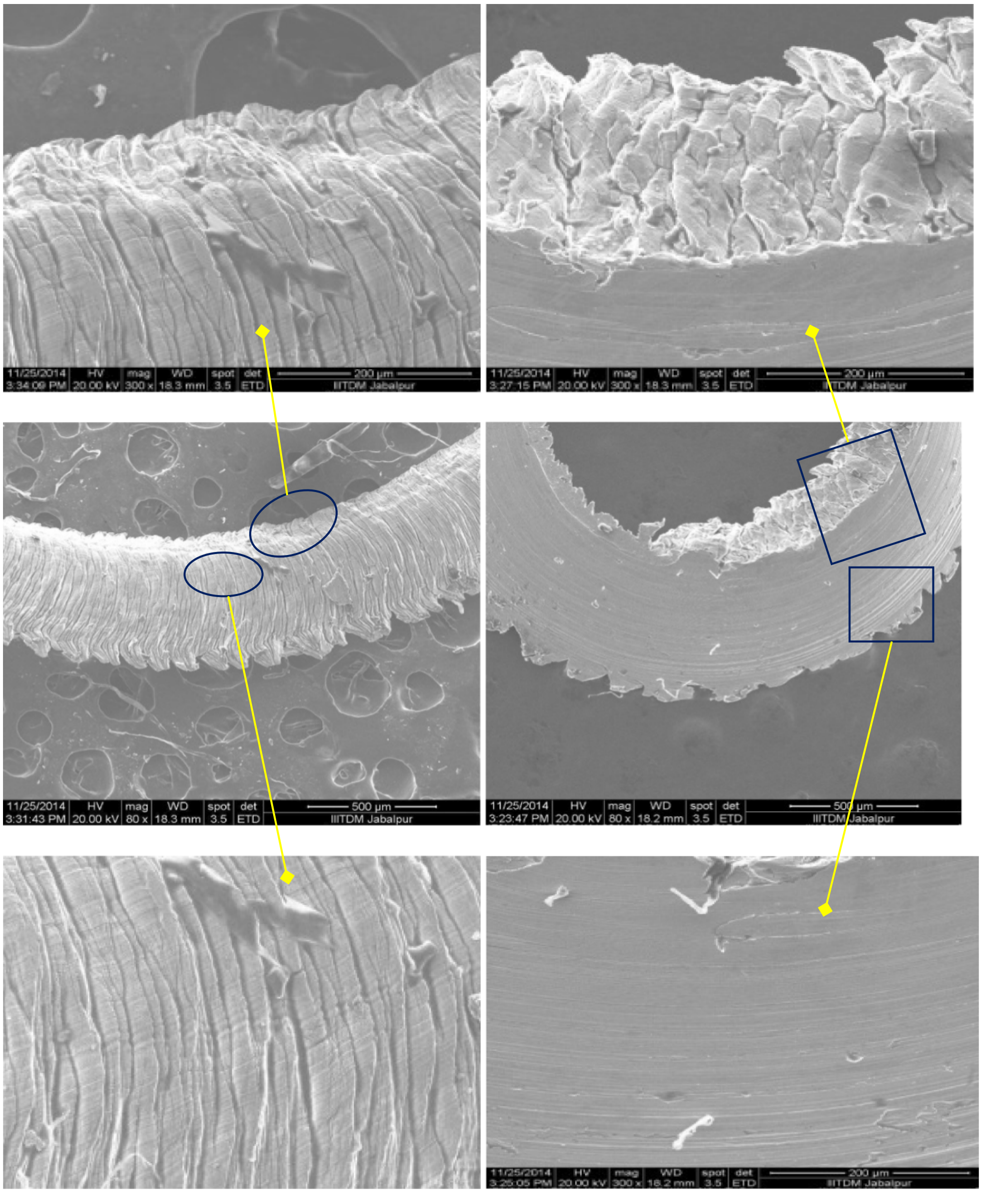


(a) (b)

Fig. 17 SEM images of chip under dry cutting condition **a** free surface, **b** back surface

rake face and the chip, which pushes the chip away from the tool face and sometimes breaks the chip after a certain length [57].

In this study, it was found that the conventional cutting lubricants failed to penetrate through the chip-tool contact zone as the chip maintained a tight contact with the tool rake face. On the other hand, the conventional cutting fluid flow was not able to flush away the chips accumulated near the cutting zone causing damage to both the cutting tool and the surface finish of the work material [58]. Figure 18b shows the underside of the chip along with its magnified images. It is evident that the conventional cutting lubricants failed to enter into the chip-tool contact zone. The chip surface generated in this cutting condition rubs on the tool rake face during machining process, thereby causing high pressure and frictional forces and generating high cutting temperature. The combination of these effects produces abrasive scratches on the underside of the chips. The coconut oil, MQL using soluble oil and MQL using coconut oil cutting conditions cause a decrease in the temperature at the cutting zone which will retain the hardness and strength of a tool during machining. Hence, these cutting conditions influence the temperature-dependent tool wear mechanisms and consequently cause a

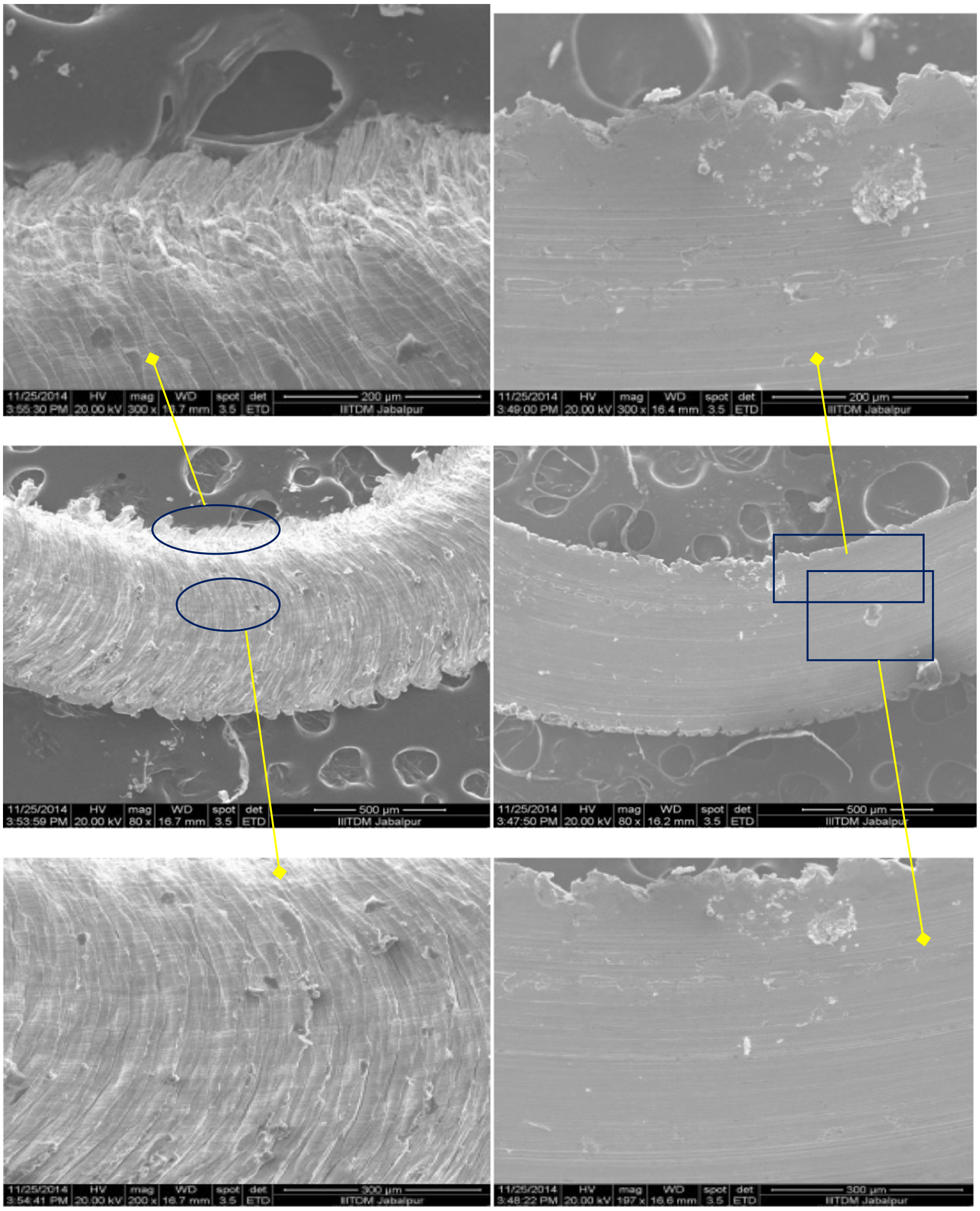


(a) (b)

Fig. 18 SEM images of chip under wet cutting condition **a** free surface, **b** back surface

reduction in the surface roughness of the workpiece material [54]. Further, the tool-work interface tends to be less affected by the chips produced in coconut oil, MQL using soluble oil and MQL using coconut oil cutting condition as the chips break off at regular interval and form discontinuous chips. As discussed in the earlier section, lesser frictional heat is generated at the secondary shear zone due to shorter chip-tool contact length [59].

Figures 19, 20 and 21 show the chip morphological images of the MQL using soluble oil, coconut oil, MQL using coconut oil cutting conditions. The SEM images of the free surfaces of chips obtained under the above-mentioned cutting environments are shown in Figs. 19a, 20a and 21a. The smaller and more uniform lamellas structure are observed, which is due to the lesser deformation. The back surface of each structure appears much brighter and smoother as seen in Figs. 19b, 20b and 21b. Coconut oil is found to be useful in removing the heat generated at the cutting zone due to its higher lubricating and cooling properties; however, some abrasive scratch marks are still observed on the underside of the chip as seen in Fig. 20b. During machining with MQL using soluble oil and MQL using coconut oil cutting conditions, these abrasive scratch marks on the underside of the chips



(a) (b)

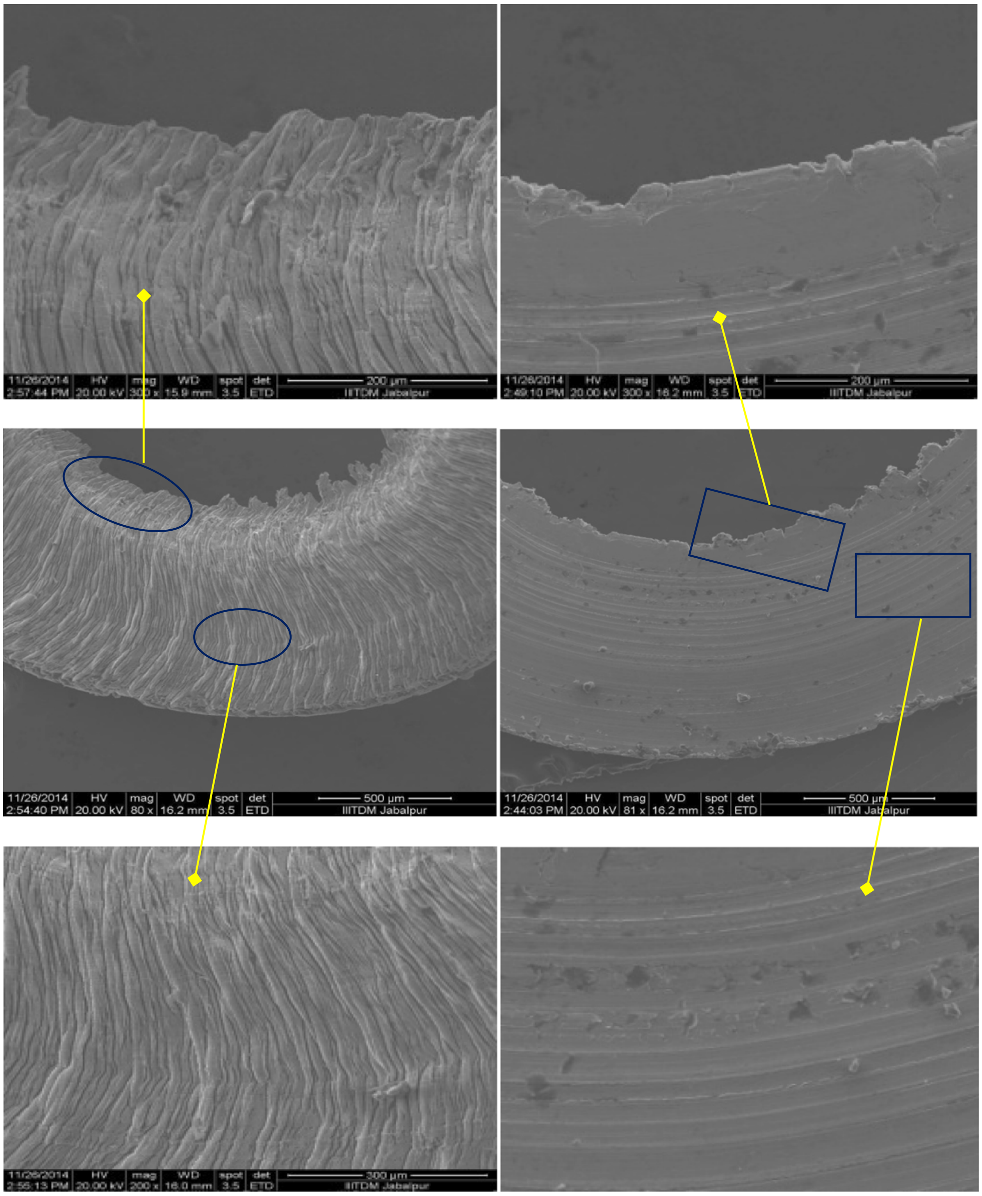
Fig. 19 SEM images of chip under MQL by soluble oil cutting condition **a** free surface, **b** back surface

are reduced as evident from Figs. 19b and 21b. This shows that the coolant in conjunction with the compressed air penetrates better in the cutting zone than any other conventional liquid coolant. The coolant and compressed air mixture mechanically lifts the chip away from the tool rake face, thereby decreasing the chip-tool contact length and rendering better cooling and lubricating properties. This causes a reduction in the possibility of crater wear and sticking of tool material on the back side of the chip and eventually reduces the adhesion and friction between the tool and the chip.

6 Summary and conclusions

The experimental studies were carried out to evaluate the influence of vegetable oil-based cutting lubricants on the cutting performance of carbide tool inserts in turning operation. The following conclusions were made from the experimental observation.

1. The turning experiments carried out under coconut oil, MQL using coconut oil and MQL using soluble oil show better machining performance.



(a) **(b)**

Fig. 20 SEM images of chip under coconut oil cutting condition **a** free surface, **b** back surface

2. Wettability angle of coconut oil was found to be 33.7°, which results in better adsorption on tool-workpiece surfaces, thereby improving lubricating properties.
3. The application of MQL using coconut oil results in a considerable decrease in friction coefficient, flank wear and auxiliary wear, causing a significant enhancement in tool life.
4. A good adsorption characteristic of coconut oil plays a very important role in the prevention of abrasion, adhesion and diffusion type of thermal sensitive wears on the flank and auxiliary surfaces.
5. A substantial improvement in surface finish was observed in the application of MQL using coconut oil, which is mainly due to reduction in wear and damage at the tool tip.
6. The analysis of chip morphology shows a significant change in the chip formation with five different machining environments. Under dry and wet machining conditions, abrasive scratch marks were clearly visible on the underside of the chips. However, these marks were gradually reduced under coconut oil, MQL using coconut oil and MQL using soluble oil

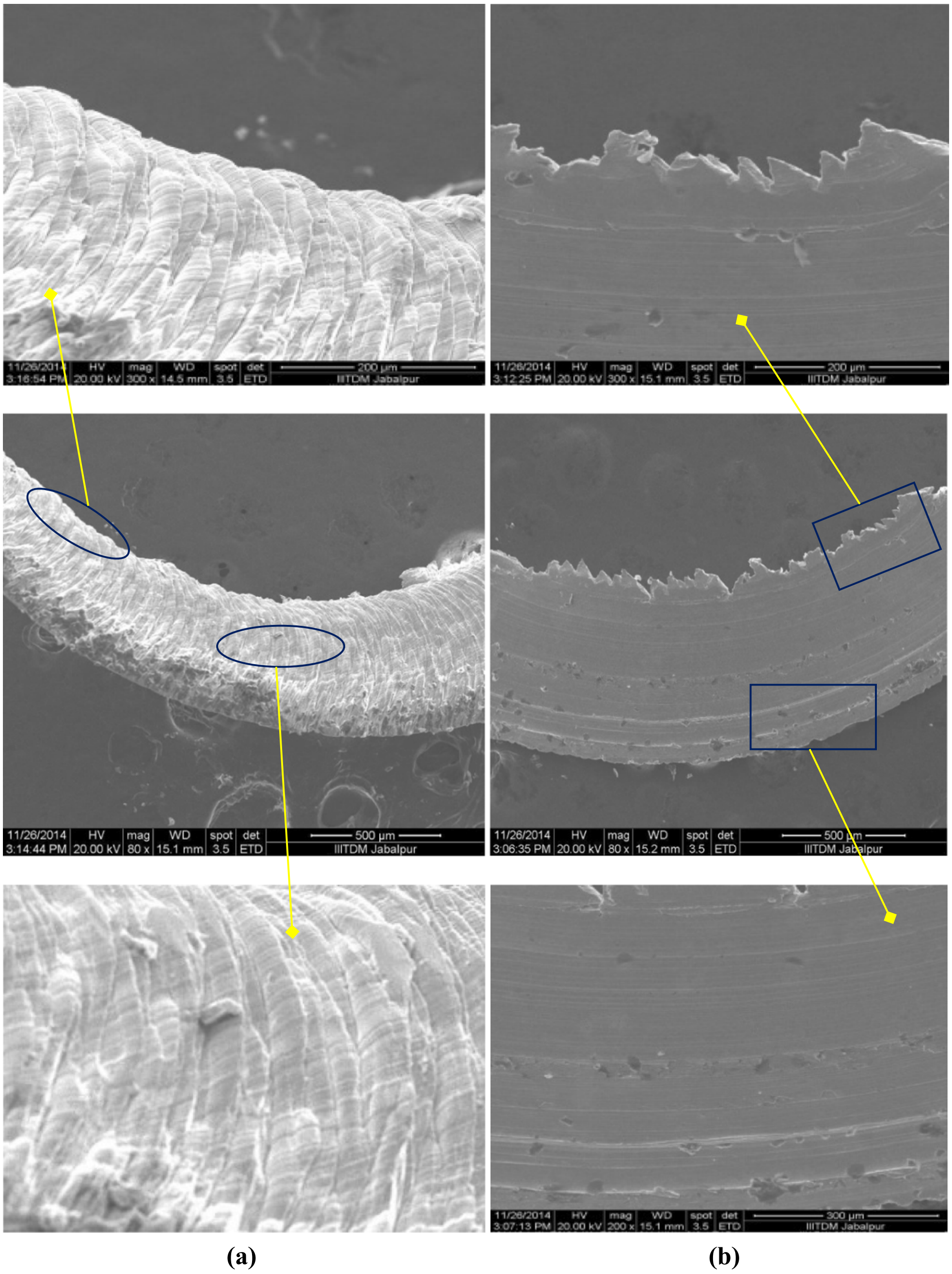


Fig. 21 SEM images of chip under MQL by coconut oil cutting condition **a** free surface, **b** back surface

machining conditions. These machining environments result in extension of the tool life by reducing the amount of heat generated and transferred to the tool.

Acknowledgements The authors gratefully acknowledge the support provided for this work by IIT Kanpur and IIITDM Jabalpur.

Compliance with ethical standards

Conflicts of interest The authors declare no conflicts of interest.

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