Development of an ultrasonic vibration assisted minimum quantity lubrication system for Ti-6Al-4V grinding

Abstract

Minimum quantity lubrication (MQL) is widely used in machining/ grinding as a competent cooling-lubrication technique owing to its advantages in terms of better cooling, lubrication, and lower coolant consumption. Ultrasonic vibration can be used to enhance the efficiency of MQL system by atomizing the cutting fluid into fine and uniform droplets. In this study, an ultrasonic vibration assisted MQL (UAV-MQL) system is indigenously developed to effectively atomize the cutting fluid using the ultrasonic vibration of a suitably designed horn. To check the effectiveness of the developed UAV-MQL system, a set of experiments have been conducted on Ti-6Al-4V alloy during surface grinding operation, and the results have been compared with dry, flood and air-assisted conventional MQL grinding process using soluble oil as a cutting fluid.

Keywords: Minimum quantity lubrication, ultrasonic, vibration, atomization, Ti-6Al-4V, MQL, grinding force, surface finish

1.0 INTRODUCTION

The excellent mechanical properties of titanium alloys make them suitable for various industrial applications. Moreover, Ti-6Al-4V is an important and extensively used titanium-based alloy. It finds applications in a wide engineering domain including aerospace, chemical, power and medical industries owing to its higher strength-to-weight ratio, relatively lower density, and superior corrosion resistance**.** However, Ti-6Al-4V is classified as “difficult-to-machine material” because of its lower modulus of elasticity, poor thermal conductivity and higher chemical reactivity (Ezugwu et al., 1997). The properties of the alloy adversely affect its product quality during the grinding process. Grinding is a widely used manufacturing process to obtain a good quality surface and a component with close dimensional tolerance. However, grinding is a high-energy consumption process that generates a substantial amount of heat during grinding. This huge amount of heat generally results in thermal damage to the ground part. Apart from this, grinding wheel wear, chip adhesion and redeposition, surface burning, and thermal stresses are the common problems occurred during Ti-6Al-4V grinding (Ezugwu et al., 2003). Up to a certain extent, these problems can be controlled and minimized with the application of cutting/grinding fluids. The grinding fluids are generally applied as flood/wet cooling in which a large amount of coolant is fed into the grinding zone. However, in flood/wet cooling, only a minute portion of the applied coolant is utilized. Moreover, wet cooling is a costly, ineffective and non-environment friendly means of grinding. It also causes serious health issues to the operator and adverse effect to machine tools. Hence, a different method of coolant application called minimum quantity lubrication (MQL) is being widely used in recent times. This technique is being used by several researchers for improved cooling and lubrication effect while grinding/machining operations (Silva et al., 2007; Setti et al., 2014; Huang et al., 2017; Tawakoli et al., 2009; Li et al., 2017). Here, a little amount of coolant along with compressed air is injected into the machining/ grinding zone. It appears to be a very popular and useful technique in the machining of different engineering materials. Tawakoli et al. (2009) investigated MQL grinding of soft and hardened steel using an air-oil mixture fed into the work-wheel contact area. They investigated the grinding performance through grinding forces, wheel wear and surface roughness parameters. They concluded that the MQL improves the grinding performance considerably by increasing wheel life and enhancing the ground part quality than dry grinding. Setti et al. (2014) reported that the MQL technique obtained a significant attention in grinding process to reduce environmental hazards by cutting fluids. It is effective in reducing the grinding forces and to obtain defect free ground surface with the improved surface finish. However, the capabilities of the MQL technique is mainly governed by the quality of cutting fluid droplets and the degree of their atomization. Park et al. (2010) and Chetan et al. (2016) conducted an extensive study to examine the droplet size and its distribution during conventional MQL technique where the cutting fluid gets atomized using air pressure nozzle. They reported that the cutting fluid droplets produced by conventional MQL system were non uniform and randomly distributed. Also, the droplet size and its distribution were mainly depending upon the air pressure, nozzle distance and flow rate of the cutting fluid. Currently, the ultrasonic atomization is being used to atomized the coolant into uniformly sized droplets. Ultrasonic assisted atomization provides a lot of advantages like smaller cutting fluid droplet sizes and their uniform distribution assisting to its easier entry into the cutting zone and offering better lubrication. In addition, the increased droplet density of cutting fluid in the cutting zone leads to high heat transfer and large wetting area. Ultrasonic atomization also provides good control over the mean droplet size. Ultrasonic atomization helps to achieve fine liquid droplets than a spray nozzle without any thermal change unlike with other atomization techniques (Kudo et al, 2017). The droplet diameter of the mist can be varied by altering the ultrasonic vibration parameters. The fine and uniformly distributed atomized droplets cover a larger surface area in the grinding zone and significantly improves the cooling and lubrication. Jun et al. (2008) studied the atomization mechanism in the micro-end milling of aluminum 7075 using an ultrasonic vibration of cutting fluid. They compared the performance of the developed system with dry and flood cooling conditions for machinability enhancement of the material. It was found that the tool life enhanced significantly using the ultrasonic atomized cutting fluids. Rukosuyev et al., (2010) designed a cutting fluid application system based upon ultrasonic atomization and discussed the effects of various nozzle geometries. They studied the consequences of mist and spray velocities upon the spray focusing quality. They concluded that the nozzle position allied to cutting zone plays a critical role in the system performance for enhanced cooling and lubrication. Ishimatsu et al. (2012) discussed the influence of excited cutting fluid by ultrasonic vibration in grinding of aluminum and alloy tool steel. They set the ultrasonic exciter between the cutting fluid nozzle and wheel to apply the vibration energy to the grinding fluid. They found that the wheel loading was prevented and the surface finish was improved. In another study, they investigated the grinding force and temperature. They reported that the grinding force and thermal escalation was reduced using ultrasonic vibration applied to cutting fluid (Ishimatsu et al., 2014). It was also found that the burn marks over titanium ground surface were prevented. Recently, Huang et al. (2016) investigated the lubrication in grinding using multi-walled carbon nanotube nanofluids dispersed with ultrasonic-assistance. They compared the results of MQL and ultrasonic MQL grinding. They concluded that the nanoparticle agglomeration restricts the accessibility of nanoparticles in the grinding zone in conventional MQL technique that hampers the lubrication effect. However, in ultrasonic MQL the nanofluid got uniformly dispersed. This has increased the lubrication effect resulting in less grinding forces and improved surface quality of the ground part. In another study by Huang et al. (2018), they developed a nanofluid/ ultrasonic atomization

MQL system and explored the effectiveness of the system during grinding of hardened mold steel. They have experimentally studied the influence of nanoparticles, nanofluid concentration, tangential velocity, table rate, nozzle angle, nozzle distance, air pressure, and spray volume on the performance of the developed system in terms of grinding force ratio, grinding temperature, surface roughness and surface morphology. They found that the nanofluid concentration contributes most to the grinding forces and surface roughness whereas the spray volume contributes most to the grinding temperature. They also suggested the optimum system parameters for the improved grinding of the hardened mold steel. The above literature discussions clearly points towards the enhancement in grinding performance using ultrasonic MQL. However, this field has not been explored much, especially during grinding operation. Hence, based on the above discussion, the present study aims to develop a UAV-MQL system and evaluate the Ti-6Al-4V grinding performance in surface grinding operation. In this work, soluble oil cutting fluid is atomized by indigenously developed UAV-MQL system during grinding operation. Effectiveness of the developed system have been examined through average grinding forces, mean surface roughness, and some microscopic analysis of the ground surfaces.

2. MATERIALS AND METHODS

2.1 UAV-MQL system

To generate the mist of soluble cutting oil, the UAV-MQL system has been indigenously designed and fabricated. The UAV-MQL system consists of an ultrasonic generator, ultrasonic horn, air compressor, air pressure regulator, fluid reservoir and flow regulator, etc. The ultrasonic horn is one of the most important elements of the UAV-MQL system. Measures should be taken to correctly design and manufacturing of the horn as improperly designed horn results in damage and malfunctioning of the transducer or ultrasonic generator (Kalita et al., 2016). The ultrasonic horns are generally half wavelength units or multiple thereof, usually based around the axial longitudinal velocity of sound within the respective component material (usually an aluminum or titanium alloy). Hence, there would be different ultrasonic frequency for different material (Graham et al., 1999). Moreover, the desired material properties for a successful horn is good resistance to fatigue, mechanical strength and better acoustic properties. An aluminum horn was specially developed to vibrate at an ultrasonic frequency of around 20 kHz. The modal and harmonic analyses of the horn have been done using ANSYS for stress and output amplitude. From the analysis, maximum stress was found to be 24 MPa (Fig. 1a) which is below the fatigue limit of Al 6061. The output amplitude was found to be 10 µm (Fig. 1b) for the given input amplitude of 5 µm. Impedance analyzer with solid squad software was also used during final manufacturing of the horn to get the desired dimensions of the vibratory horn. A pictorial view of the developed horn and a schematic representation of the UAV-MQL setup are shown in Fig. 1c and 1d respectively. The cutting fluid is constantly supplied from the reservoir by gravity to the vibratory horn through the passage made in the horn at 250 ml/hr flow rate. Consequently, the cutting fluid gets atomized into very fine droplets by the ultrasonic vibration of the horn. The atomized droplets are then focused into the grinding zone using compressed air at a pressure of 4 bars (Tawakoli et al., 2009; Sadeghi et al., 2009; Huang et al., 2018).

2.2 Mechanism of cutting fluid droplets formation

The droplet formation mechanism is mainly governed by the cavitation and capillary wave hypothesis (Kudo et al., 2017). As per the cavitation hypothesis, due to the high-intensity ultrasonic vibrations, cavitation bubbles are formed. When these bubbles strike the surface of the liquid, they form further bubbles thus initiating a chain reaction. Another is the capillary wave hypothesis, in which, due to ultrasonic vibrations, high amplitude capillary waves are formed. When these capillary waves become unstable, they tear the crests and troughs apart thus generating very fine droplets. These fine droplets enter into the cutting zone and form a thin film of lubricant over the surface of the workpiece during grinding. It also results in the reduction of relative distances between the droplets leading to an increased number of droplets entering into the grinding zone. Fig. 2a and 2b show the stereo zoom microscope (SZM) images of cutting fluid droplets distribution obtained in the case of a conventional and ultrasonic vibration assisted MQL system respectively. It can be seen that the cutting fluid droplets obtained in case of UAV-MQL are smaller in size and uniformly distributed as compared to those obtained in conventional MQL. The smaller droplet size leads to the easier entry of cutting fluid droplets in the grinding region. Also, it covers the maximum area of the workpiece to be ground and forms a thin layer of lubricant over the surface of the workpiece which enhances the cooling-lubrication effect of the coolants to a larger extent.

2.3 Experimental details

CNC surface grinding machine (*SMARTH1224, Chevalier*) was employed to conduct the grinding experiments using a silicon carbide grinding wheel. A picture of the experimental setup is shown in Fig.3. KISTLER 9257B dynamometer has been used for online measurement of the grinding forces. A surface profilometer (Talysurf, Taylor Hobson, UK) has been used to measure the ground surface roughness. The ground surface was further analyzed qualitatively using a stereo zoom microscope (make: Carl Zeiss). The SEM analysis of ground surface and grinding chip has been done to study the grinding mechanism in case of UAV-MQL grinding condition. The grinding wheel is dressed before every run to maintain the uniformity. The grinding conditions are described in Table 1.

2.4 Design of Experiments

While grinding Ti-6Al-4V alloy, the variable inputs selected were grinding wheel speed, table speed and depth of cut whereas the output responses being a tangential force, normal force and surface roughness. The Box Behnken Design (BBD) of response surface methodology (RSM) has been used to plan the experimental runs (Montgomery, 2008). It takes into consideration 3 levels of each factor of input variables during grinding experiments. These factors are suitably chosen based on the preliminary experimentations as shown in Table 2. Grinding experiments have been performed at the mentioned process parameters with flood cooling, conventional MQL and UAV-MQL grinding mode and the results were compared. The average response values of three experiments for each run have been used for analysis. The ANOVA analysis and main effects plot obtained by MINITAB17 has been used to plot the experimental results.

3.0 RESULTS AND DISCUSSIONS

3.1 Tangential grinding force

Tangential force is an extremely important parameter in the grinding process. It has a greater influence on the material removal and the sliding and plowing of the abrasive grits. It plays a major role in deciding the energy requirements in the grinding and to decide the grinding difficulties of different materials. It is mostly dependent on the lubrication effects during grinding. The average value of the tangential force during grinding with different process parameters in different environments- Flood cooling techniques (FCT), conventional MQL and UAV-MQL are shown in Fig. 4. It is observed that the conventional MQL and UAV-MQL produced lower grinding forces than FCT grinding. Moreover, the UAV-MQL grinding has generated the lowest tangential forces. The reason may be that the mist generated from UAV-MQL produce fine droplets of uniform shape and size which can be dispersed uniformly in the grinding zone and forms a uniform protective layer of cutting fluid. This makes the penetration and sliding of abrasive grains easier and provides proper lubrication to decrease the friction between the abrasive grits and workpiece, resulting in lower tangential forces. The nonuniform cutting fluid droplets distribution in conventional MQL limits the accessibility of coolant droplets in the grinding region as depicted in Fig. 5a. However, during UAV-MQL, the ultrafine droplets penetrate the grinding zone effectively resulting in better cooling and lubrication between the workpiece-grit interfaces. It also aids in keeping the abrasive grit sharper for a longer duration due to better accessibility of cutting fluid droplets in the grinding region including the space between the fractured abrasive grains as represented in Fig. 5b. Hence, the lowest tangential forces were observed in case of UAV-MQL grinding.

3.2 Normal grinding force

It represents the ease of penetration of abrasive grits into the workpiece surface. The normal grinding force obtained during grinding with different process parameters in different environments- Flood cooling techniques (FCT), conventional MQL and UAV-MQL are shown in Fig. 6. It can be seen that the normal forces obtained during UAV-MQL are lower than FCT and conventional MQL grinding. In case of conventional MQL and UAV-MQL grinding, effective penetration of cutting fluid to the grinding region results in proper cooling and lubrication. So, the grit penetration becomes easier which helps in the reduction of normal grinding. Further, in UAV-MQL, the cutting fluid can access the microfracture of abrasive grits to keep them sharp for longerduration which also helps in the reduction of normal forces.

3.3 Surface roughness

The surface roughness obtained during grinding with different process parameters under conventional MQL and UAV-MQL grinding environment is shown in Fig. 7. It has been found that the UAV-MQL grinding results in lower average surface roughness while grinding with all the process parameters. These results show that the UAV-MQL grinding is capable of getting improved workpiece surface quality than MQL grinding. Figure 8 (a and b) shows the variation in surface profiles and surface roughness values on the ground surfaces in MQL and UAV-MQL conditions respectively. It can be observed that the surface roughness profile obtained during UAV- MQL grinding has better uniformity and lower surface roughness value than that obtained during MQL grinding. This also points towards the formation of an effective lubricating layer by cutting fluid droplets between the contacting surfaces in case of UAV-MQL grinding. Figure 9a, 9b, 9c and 9d shows the ground surface micrographs observed using stereo zoom microscope during dry, Flood cooling technique (FCT), conventional MQL and UAV-MQL grinding environments respectively. It was found that during dry grinding conditions there are few burning marks and surface defects observed on the Ti-6Al-V4 workpiece. The severity of surface defects got reduced during FCT and further during MQL conditions; still, there were few ploughing and rubbing marks observed in FCT and MQL grinding. However, such marks were not observed in the case of UAV-MQL grinding. Moreover, a uniform and defect free surface with enhanced lubrication effect can be revealed by the SEM image of the ground surface during UAV-MQL grinding as shown in Fig. 10. It can be seen that a uniform grinding marks and better surface quality of the ground surface is obtained during UAV-MQL grinding. This can be achieved through the uniform cutting fluid layer formed over the workpiece surface via the uniformly distributed fine droplets of the cutting fluid during UAV-MQL. This helps in reducing the plowing, rubbing and promoting the shear action by sharp abrasive grits. The improved quality of the ground surface in UAV-MQL grinding is beneficial for the performance improvement of the ground product. The aptness of the UAV- MQL grinding has also been noticed from a long and shear type of chips produced during UAV-MQL grinding as shown in SEM image of the grinding chips (Fig. 11). Distinct shear marks can also be seen over the chip surface. These are the ideal chips generally produced by shearing action where less force and energy is required during grinding. This is the most suitable mode of grinding which is also depicted from the lower grinding forces obtained during UAV- MQL. It was possible due to the retention of abrasive grit sharpness which adds to the effectiveness of UAV- MQL grinding.

4.0 CONCLUSIONS

In the present study, the effectiveness of UAV-MQL grinding of Ti-6Al-4V alloy has been studied using indigenously designed and developed UAV-MQL setup. Experiments were carried out using flood cooling technique, MQL technique, and UAV-MQL technique. Grinding characteristics were studied using the online measurement of forces during grinding, surface roughness, and the morphology study of ground surface and grinding chips. The following major influences may be drawn from this study:

- The smaller and uniform size cutting fluid droplets were obtained in the case of UAV-MQL as compared to the conventional MQL. Smaller droplet size leads to easier entry and uniform distribution of cutting fluid droplets in the grinding region.
- Significant reduction in cutting forces was observed during UAV-MQL grinding as compared to other grinding technique.
- The surface quality of the workpiece has also been improved using UAV-MQL grinding. The rubbing, ploughing and burning marks as observed during dry, FCT and conventional MQL grinding were found to be significantly eliminated in case of UAV-MQL grinding.
- The UAV-MQL grinding exhibited efficient cooling and lubrication effect by producing shearing types of chips.
- Overall, it can be concluded that the UAV-MQL has a tremendous potential for improving the grinding performance of Ti-6Al-4V.

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Table 1: Grinding conditions

Parameters	**Description**
Grinding wheel	CG-60-K-5-V
Workpiece material, dimensions	Ti-6Al-4V, 60 × 60 × 10 mm
Grinding kinematic parameters	Grinding wheel speed: 10, 15, 20 (m/s)
	Table speed : 3, 6, 9 (m/min)
	Depth of cut: 5, 10, 15 (µm)
Dressing parameters	Wheel speed: 1000 rpm
	Dressing depth: 5 passes of 10 µm each
	Dressing lead: 250 mm/min
Cutting fluid	Soluble cutting oil (Mineral oil mixed with water in the ratio 1:20)

Table 2: Details of experimental process parameters

Factors	**Symbol**	**Unit**	**Levels**		
			-1	**0**	**1**
Wheel Speed	V_S	m/sec	10	15	20
Table feed	V_W	m/min	3	6	9
Depth of cut	a_e	µm	5	10	15

LIST OF FIGURES

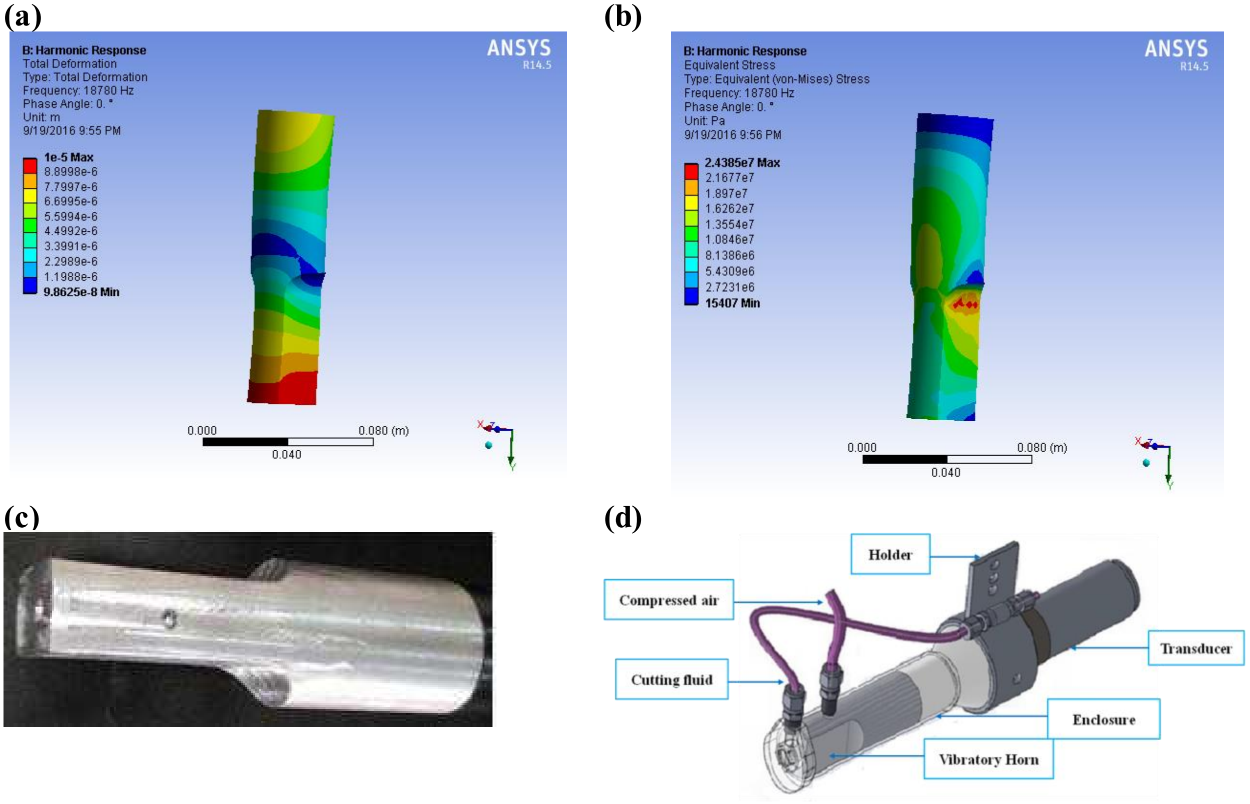

Fig. 1. (a) Output of deformation analysis (b) Output of stress analysis (c) Photograph of the developed horn (d) Schematic diagram of the developed UAV-MQL setup (Madarkar et al., 2018).

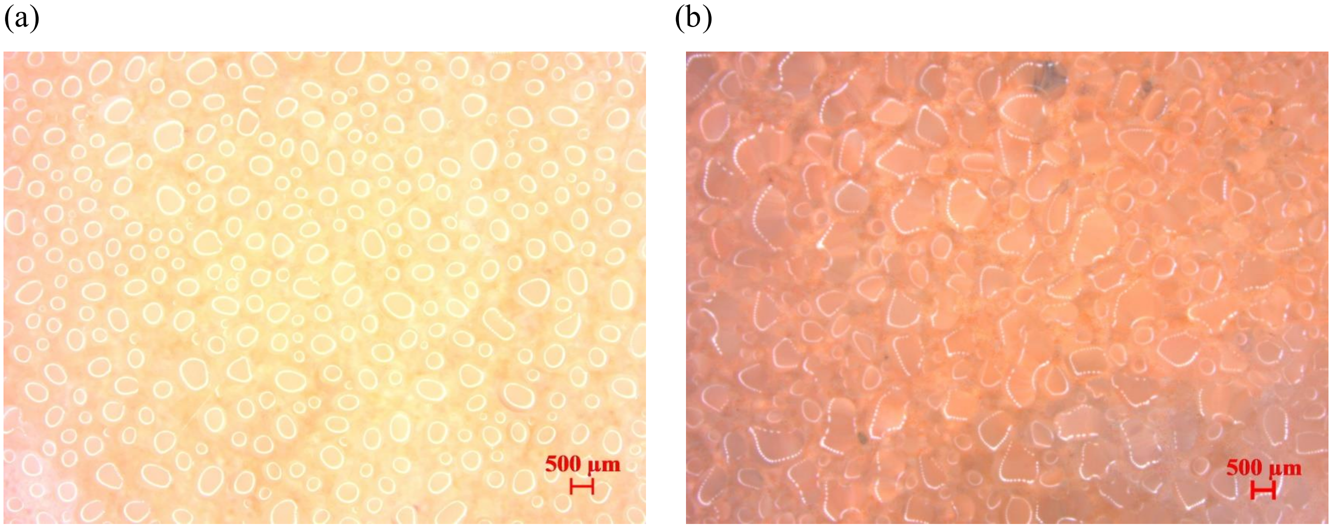

Fig. 2. SZM micrographs of droplets obtained (a) With traditional MQL setup (b) UAV-MQL setup at 7.5X magnification

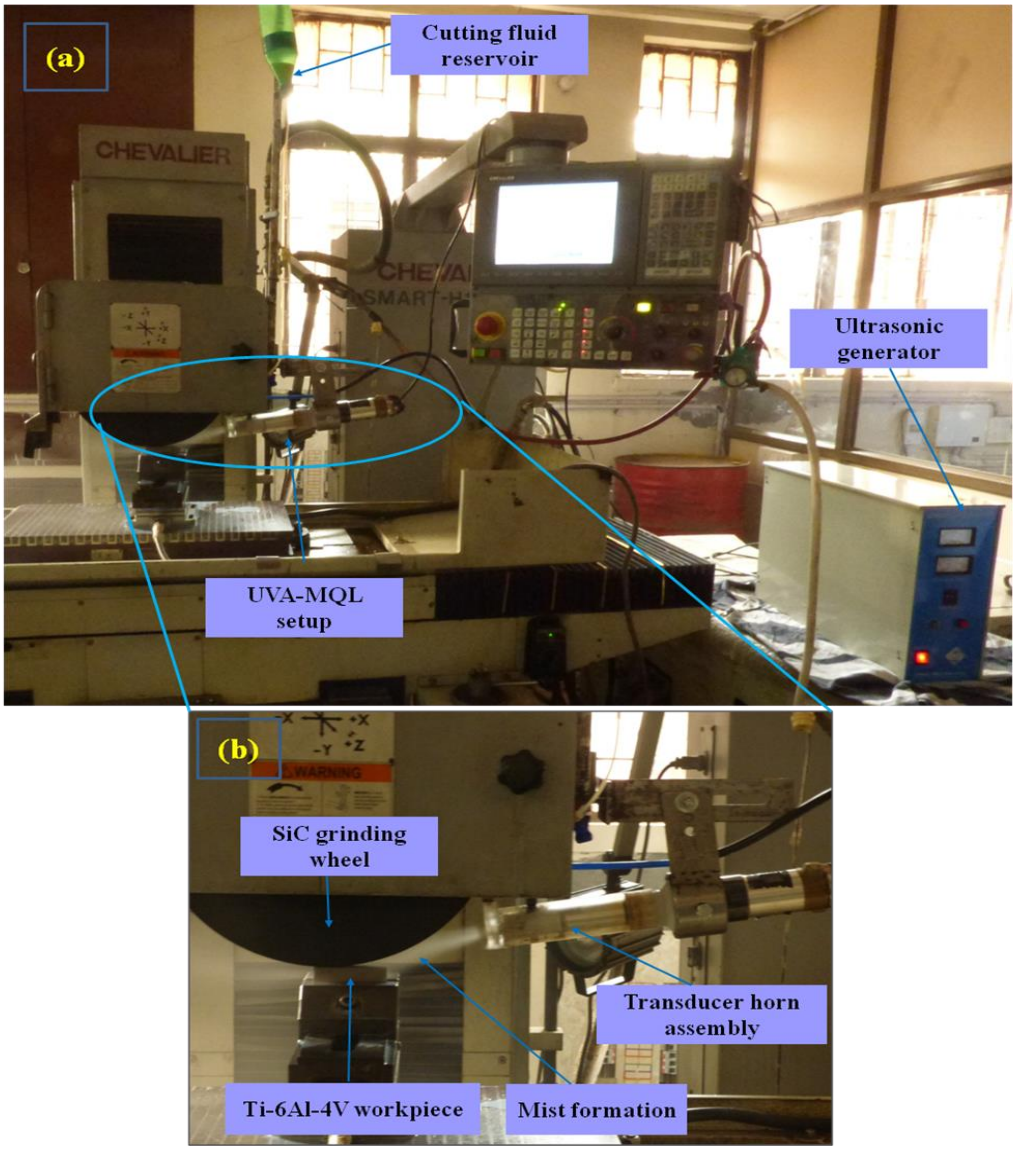

Fig. 3. A photograph of experimental set up: (a) Grinding Machine, (b) UAV-MQL setup

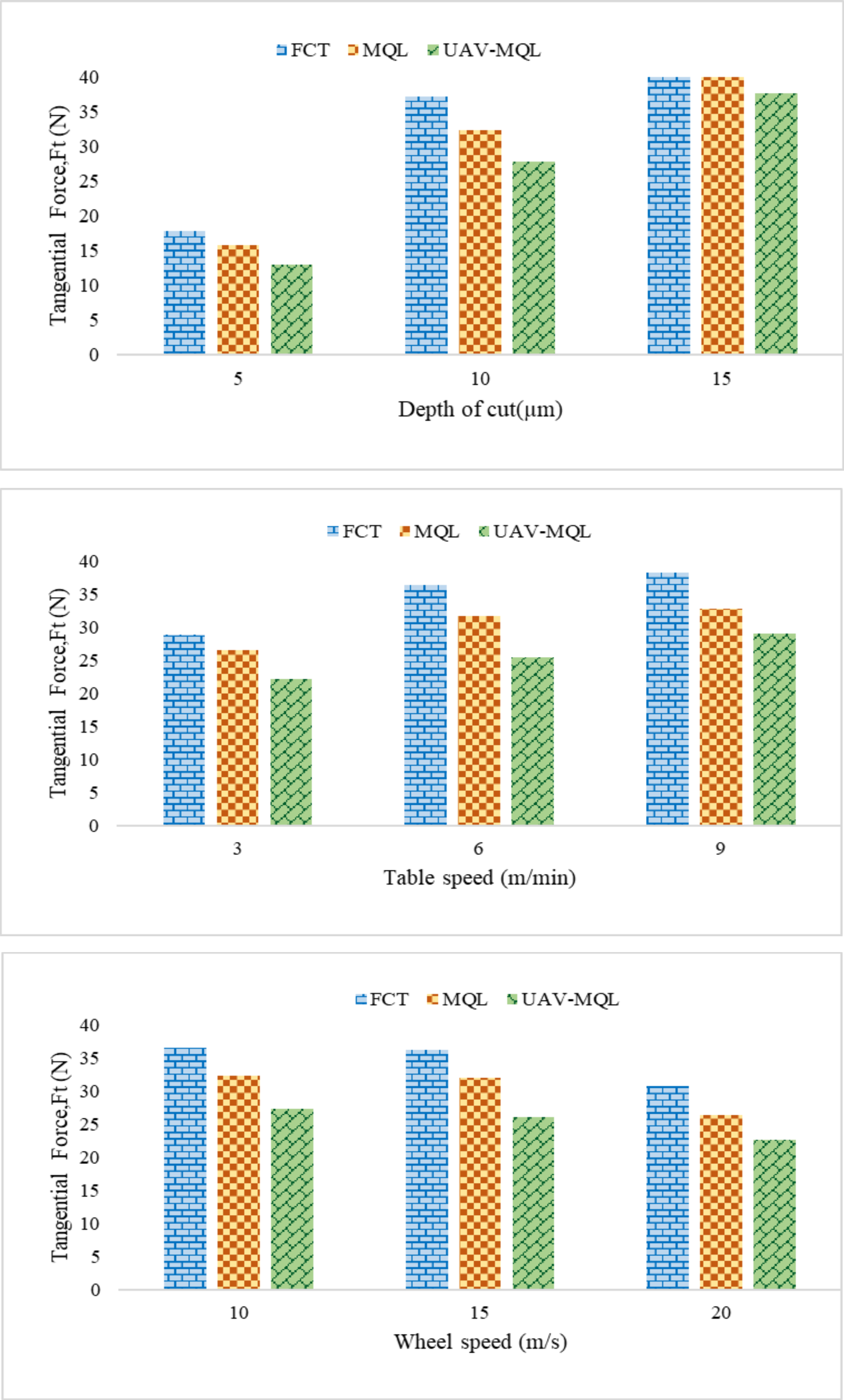

Fig. 4. Tangential grinding forces at selected process parameters in different grinding environments

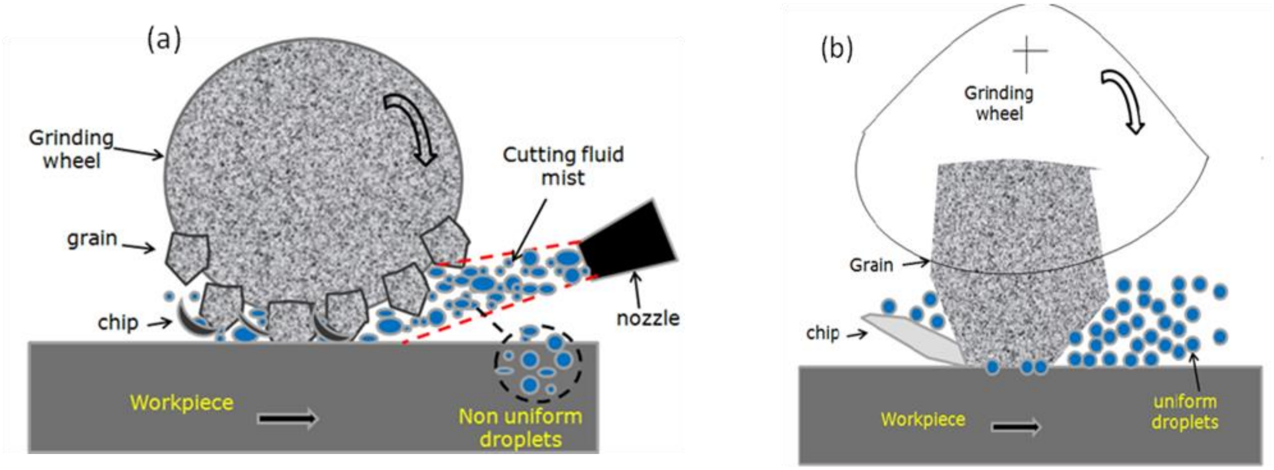

Fig. 5.Schematics of coolant droplets in grinding region during (a) Conventional MQL grinding (b) UAV-MQL grinding (Madarkar et al., 2018)

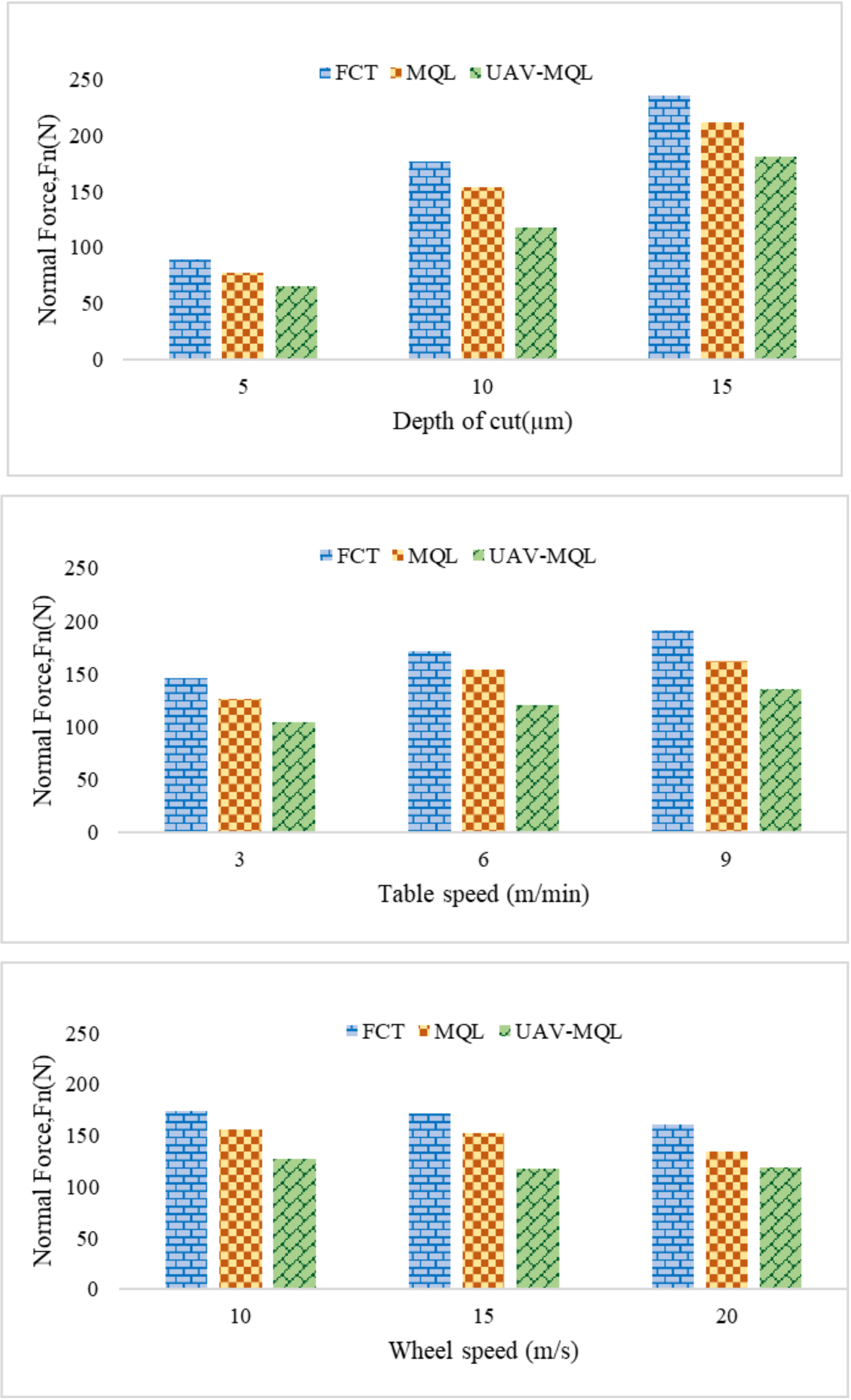

Fig. 6. Normal grinding forces at selected process parameters in different grinding environments

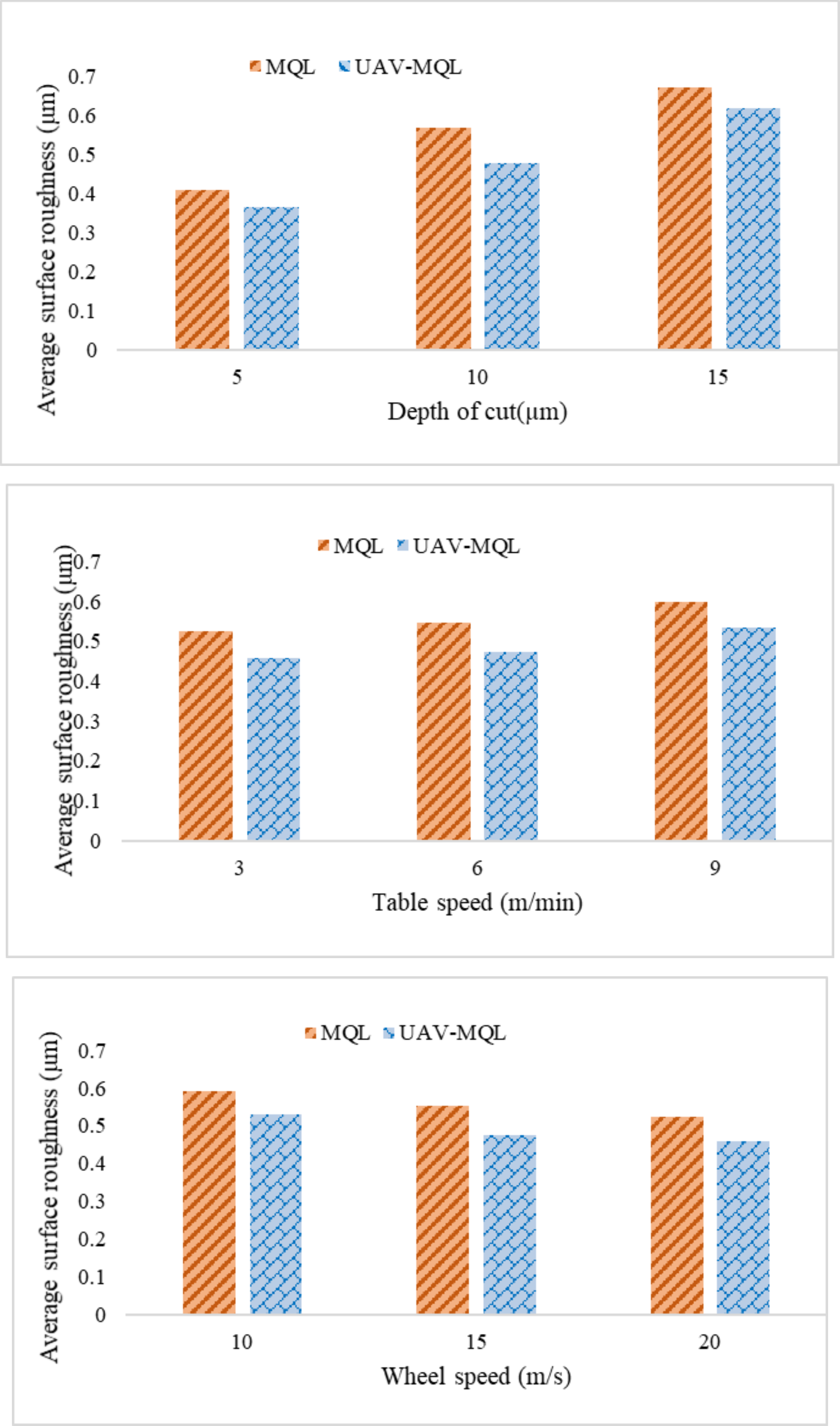

Fig. 7. Variation in average surface roughness with different process parameters under different grinding environments

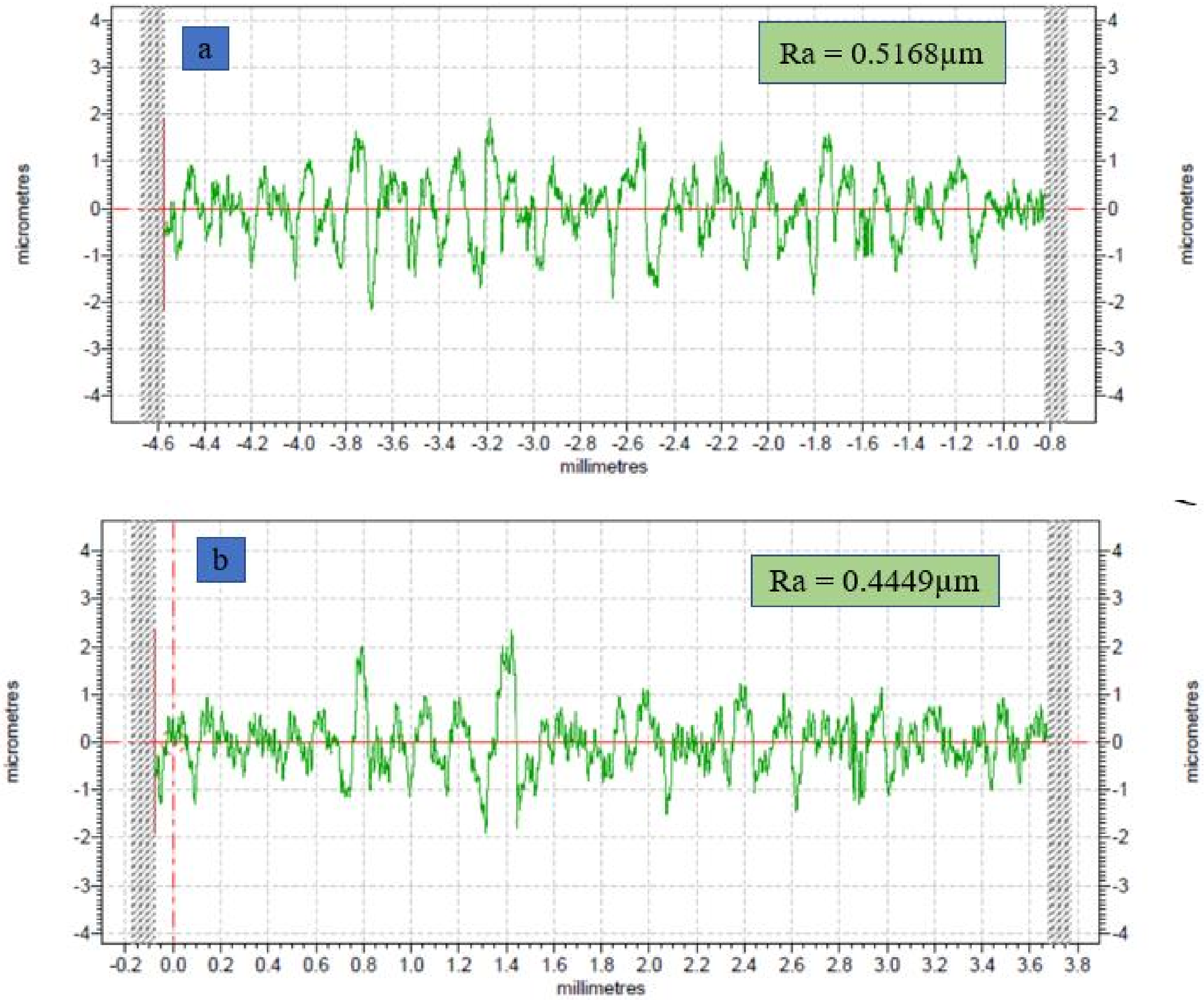

Fig.8 . Surface roughness profile (Vc= 20m/s, Vw= 6m/min, DOC= 10 μm) during (a) MQL grinding, (b) UAV- MQL grinding

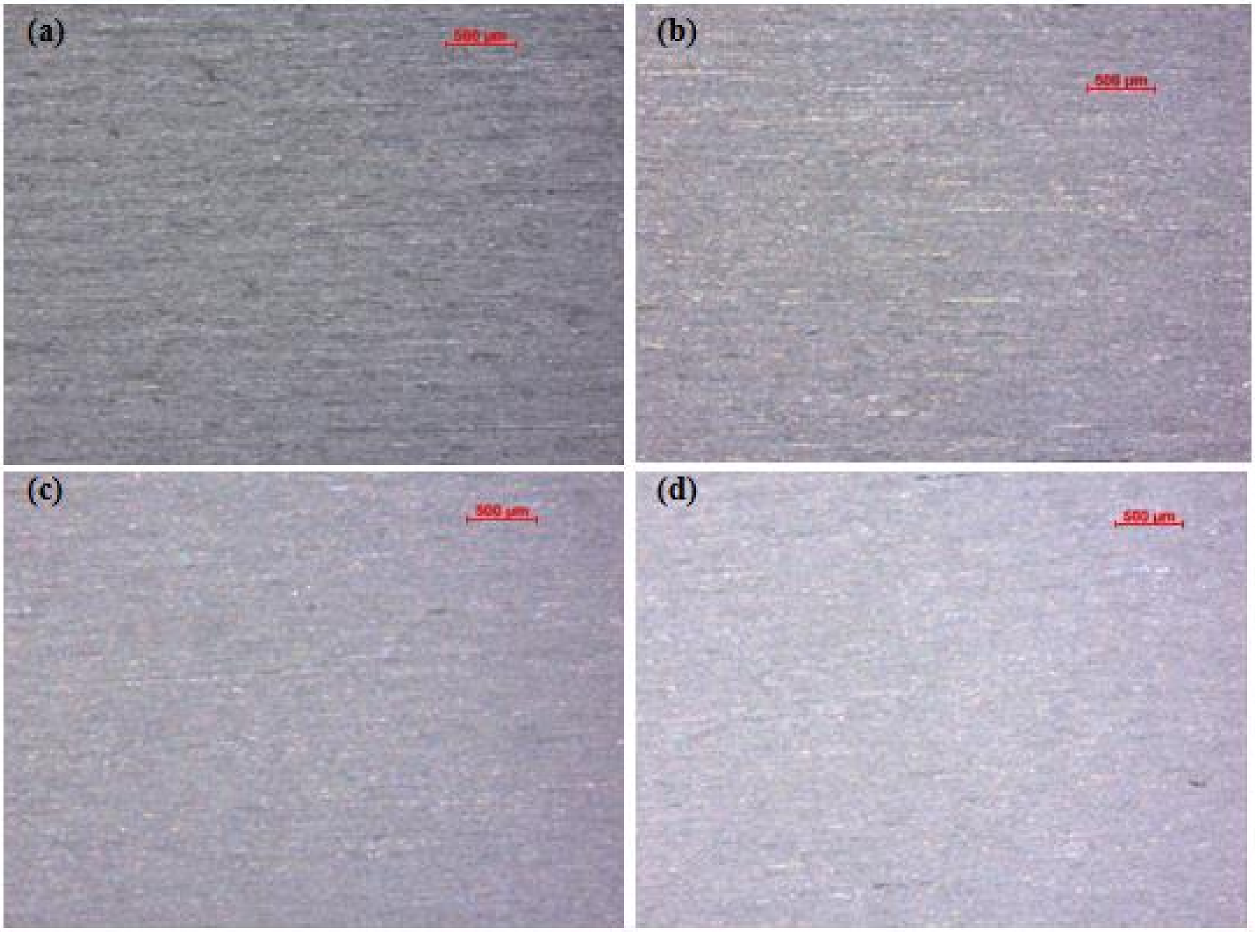

Fig. 9. Surface micrographs at 25X after (a) dry, (b) Flood cooling technique, (c) conventional MQL and (d) UAV-MQL grinding condition at depth of cut = 10 micron; table speed = 6 m/min and wheel speed= 15m/s.

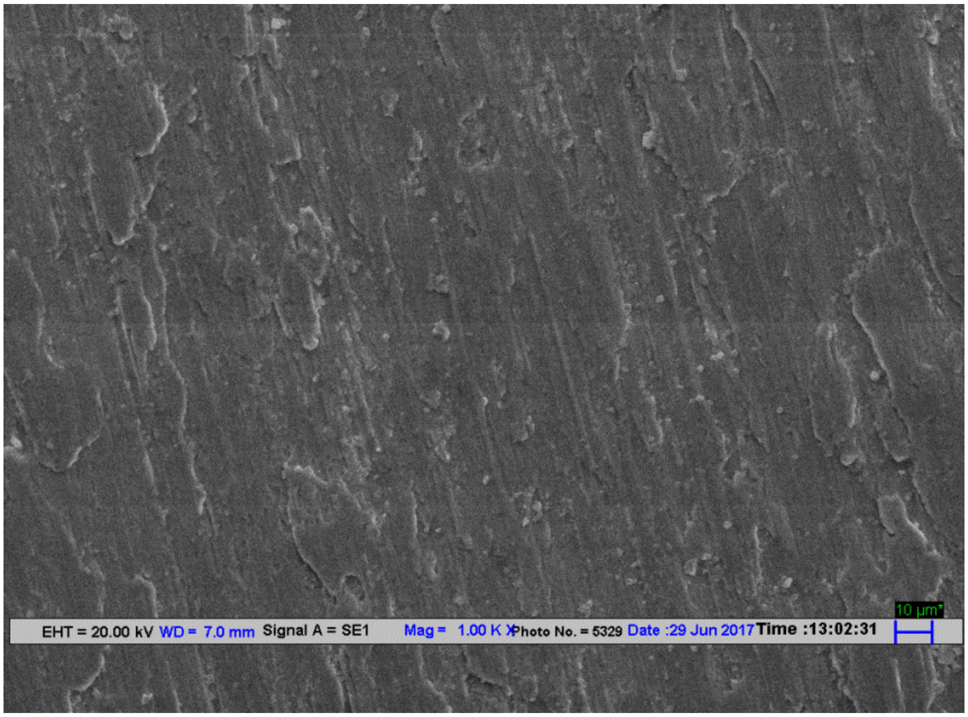

Fig.10. SEM image of the ground surface at 500X in UAV-MQL grinding environment

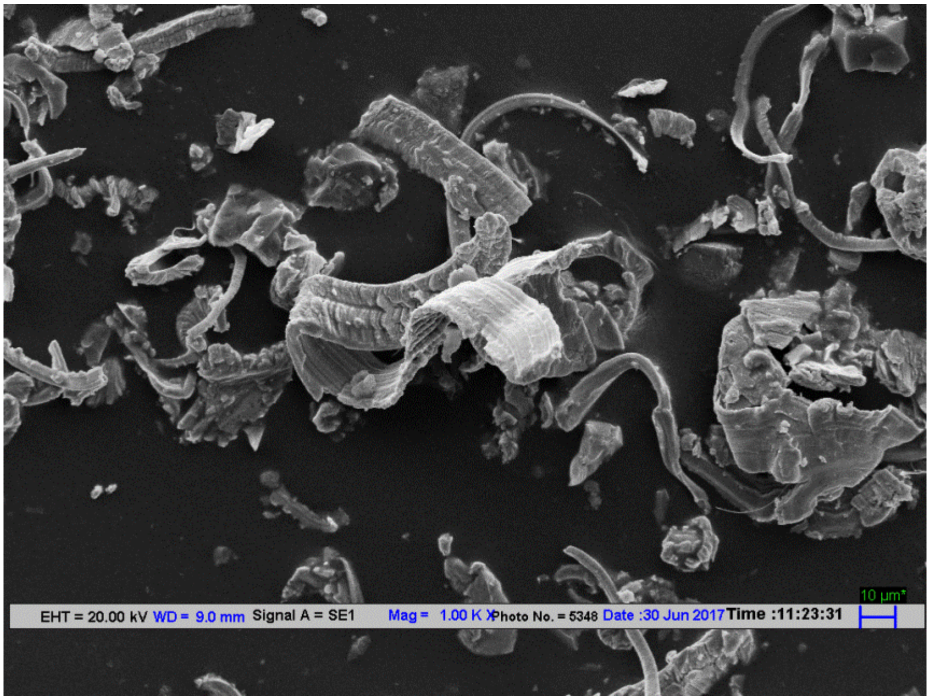

Fig. 11. SEM image of grinding debris at 1000X in UAV- MQL grinding environment