Comparison of Machining Performance under MQL and Ultra-High Voltage EMQL Conditions Based on Tribological Properties

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Abstract

This novel work presents the comparison of a newly developed ultra-high voltage electrostatic minimum quantity lubrication (EMQL) using a customized nozzle with the MQL technique as an alternative cooling/lubricating method in turning processes of 15-5 PHSS. The optimum voltage for EMQL within the range of 0-25 kV has been identified based on tribological performance. Besides, surface roughness has been measured to identify the impact of electrostatically charged mist for turning 15-5 PHSS. Finally, tool wear tests are performed for MQL and EMQL at optimized voltage. The EMQL at optimized electrostatic voltage resulted in 38% decreased tool wear as compared to conventional MQL for 2400 mm cutting length.

Keywords: Electrostatic Minimum quantity lubrication; Stainless steel; Turning; Tribology

1. Introduction

The costs associated with cutting fluids form about 17% of total machining cost [1]. This includes preparation, maintenance, treatment and disposal of the cutting fluids as well as space and energy requirements for storage and recirculation. Apart from it, bacterial and fungal growth in water-based cutting fluids also promotes risk to workers' health. In this context, there is an urge to develop alternative sustainable cooling/lubrication techniques that provide higher productivity without affecting the environment and workers' health [2,3].

MQL is one of such alternative cooling/lubrication techniques in which, cutting fluid is applied in the form of mist through pressurized air. In MQL technique, a minute amount of cutting fluid (5-20 ml/h) is used as compared to flood machining (30 l/h) [4]. The majority of oil used in MQL evaporates and burns at cutting zone, minimizing the need for cleaning workpiece and cut chips after machining. To increase the sustainability of MQL technique, vegetable-based cutting fluids are increasingly employed as a substitute to petroleum and synthetic oils. These cutting fluids are a prominent option to replace crude oil-based cutting fluids because of their properties such as non-toxicity, enhanced adsorptivity and biodegradability [5]. It was observed higher flash point of soya-bean based cutting fluid (320 °C) as compared to other petroleum-based cutting fluids (216 °C). It lowers the generation of smoke which is beneficial to the health of operator. Besides, it forms a high strength oil film on substrate which increases the lubricity and hence low friction at tool-chip interface is achieved [6]. The better machining performance in terms of lower specific grinding force and energy consumption was observed when a mixture of castor and soya-bean based cutting oil was used in MQL as compared to the mixture of castor oil with other vegetable-based cutting oils like maize, sunflower, peanut, palm and rapeseed [7]. It was found lower cutting zone temperature and surface roughness when soya-bean based cutting oil was used in MQL as compared to dry and mineral oil-based flood machining for turning AISI 4340 steel [8]. With these views, soya-bean based cutting oil has been used in this study. However, the penetrability and cooling capability of MQL are limited, which can often result in high heat generation. This not only promotes rapid tool wear but also degrades the surface integrity of workpiece.

To overcome these limitations, a variant of MQL, namely Electrostatic Minimum Quantity Lubrication (EMQL) technology, is developed. In this method, mist particles are electrically charged before reaching the cutting zone by combining two technologies, namely "Electrostatic Spraying" and MQL. The finer and controlled oil particles generated by EMQL enhance the machining performance. The effect of MQL and electrostatic spray on a substrate has been illustrated in Fig. 1. Besides, charged oil particles improve penetrability and wettability at the cutting zone resulting in improved lubrication. In practice, the charged oil particles not only increase wetting area but also promote lubrication through the formation of a metallic oxides layer.

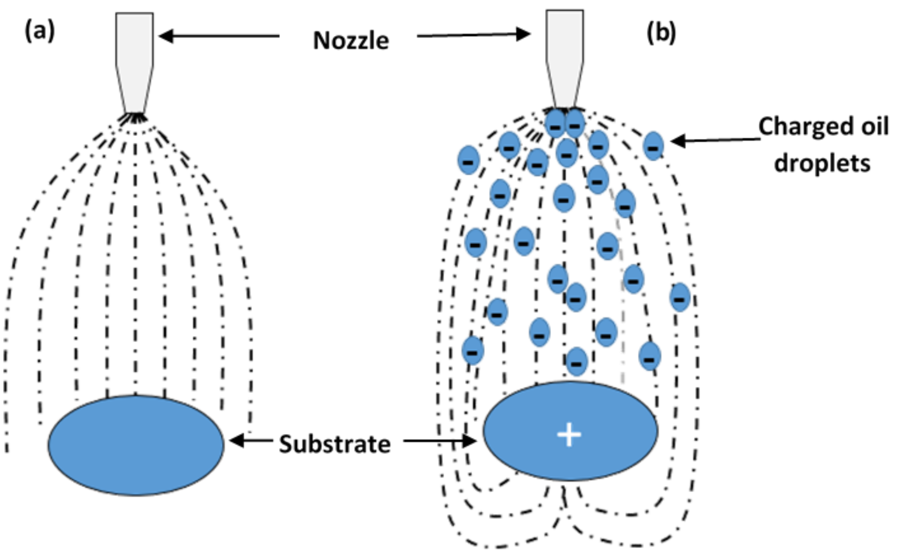


Fig. 1 An illustration showing the effect of **(a)** MQL and **(b)** Electrostatic spray on a substrate

Huang et al. [9] compared the tribological properties of EMQL technique with a change in voltage up to 12 kV. The optimum voltage, oil consumption and air-pressure were found to be 7 kV, 10 ml/h and 0.3 MPa, correspondingly. Reddy and Yang [10] compared electrostatic solid lubrication (ESL) at 5.5 kV with dry and MQL techniques for drilling process of SCM 440 steel by measuring cutting force, tool wear, surface roughness and hole diameter. The ESL resulted in 80% and 12.5% reduction in tool wear in contrast to dry and MQL machining, correspondingly. Lv et al. [11] compared near to dry machining and graphene nanoparticles immersed EMQL at 6 kV for end milling AISI 1040 steel. Improved tribological and droplet qualities viz. friction coefficient (*CoF*), droplet diameter and wetting angle were observed using EMQL, which improved machinability. Xu et al. [12] compared near to dry machining and EMQL techniques for grinding Cr12 die steel based on cutting force, surface roughness, microhardness and grinding ratio. A superior capillary effect and hence better penetration of grinding fluids observed in EMQL resulted in lower cutting force, microhardness, surface roughness with a 24.8% increment in the life of grinding wheel as compared to MQL technique.

From the above literature, it can be concluded that EMQL is found to enhance tribological and machining performance in comparison to MQL machining. However, the investigations are limited to 15 kV and higher voltages are not studied. Besides, simplistic approaches are used for charging the cutting oil by installing a wire inside an MQL nozzle [9]. This paper compares cutting fluid strategies, namely MQL and EMQL for charged mist particles from 0 to 25 kV by delivering the soya-bean based vegetable cutting oil through an electrically charged copper pipe. The comparison is based on tribological properties and machining performance in turning 15-5 PHSS.

2. Experimental Details

2.1. Experimental setup

By considering the previous usage of FRL unit to generate mist for MQL technique [13], Fig. 2 (a) and (b) describes the components and working of FRL unit used in this study.

The mist having the desired quantity of oil at required air-pressure can be achieved by FRL unit. This function is performed by its three subunits viz. filter, regulator and lubricator. As shown in Fig. 2 (a) and (b), air coming from compressor is filtered to remove dust, vapor and oil particles by cartridge fitted in filter. The drain valve is provided to remove the vapor, dust and emulsion formed due to a mixture of water particles and oil received from the air compressor. After cleaning the air, it is compressed by a diaphragm-type pressure regulator equipped with pressure gauge.

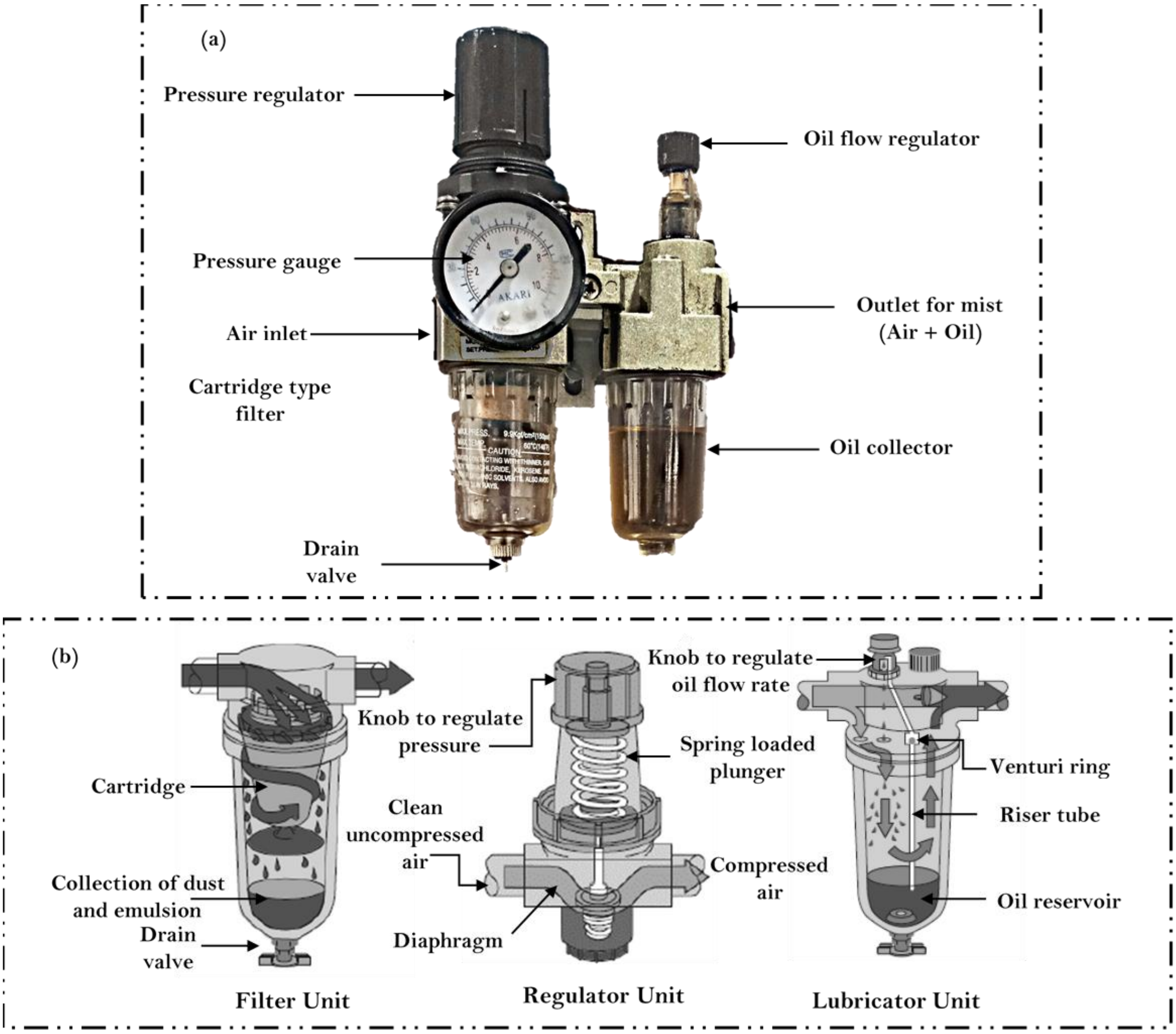


Fig. 2 Image of **(a)** Actual FRL unit used in the study and **(b)** Illustration of filter, regulator and lubricator unit with their components [14]

In regulator, spring-loaded plunger is fitted and air is compressed by adjusting the space between plunger and diaphragm. To generate the mist, lubricator unit mixes oil droplets in air by venturi effect. At the venturi ring, the velocity of air is increased generating vacuum and oil is drawn from the oil collector to upper part of lubricator by pressure difference. Finally, the mixture of oil and air exits at outlet of lubricator unit. The mist is charged by passing through an electrically charged copper pipe and sprayed into the cutting zone using a 2 mm diameter nozzle. The customized EMQL power source capable of generating ultra-high voltage up to 25 kV has been integrated with an MQL setup to charge the mist. Fig. 3 presents the experimental setup used for machinability test. Table 1 describes the EMQL parameters investigated in this study.

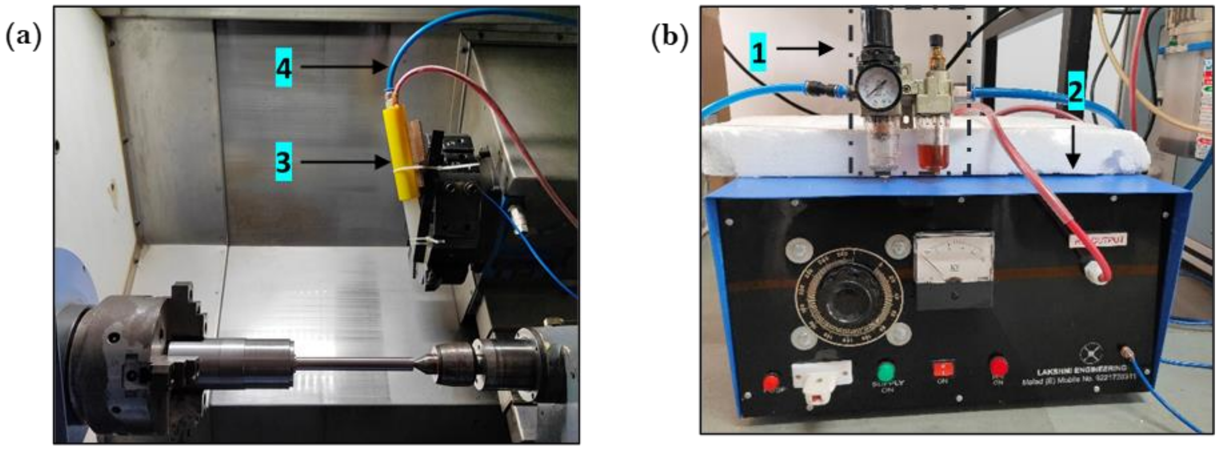


Fig. 3 An image for **(a)** Experimental setup of machinability test with **(b)** EMQL power source where **(1)** FRL unit **(2)** EMQL power source **(3)** Nozzle and **(4)** High-electrostatic voltage cable

Table 1 Description of EMQL machining parameters

Parameter	**Description**
Cutting oil	90% soya-bean oil, 5% antioxidant and 5% extreme pressure (EP) additives, Viscosity: - 30 - 34 cSt at temperature of 40 °C
Flow rate	14 ml/h
Air pressure	5 bar
Nozzle distance	20 mm from the rake face of cutting tool
Electrostatic voltage	0, 5, 10, 15, 20 and 25 kV

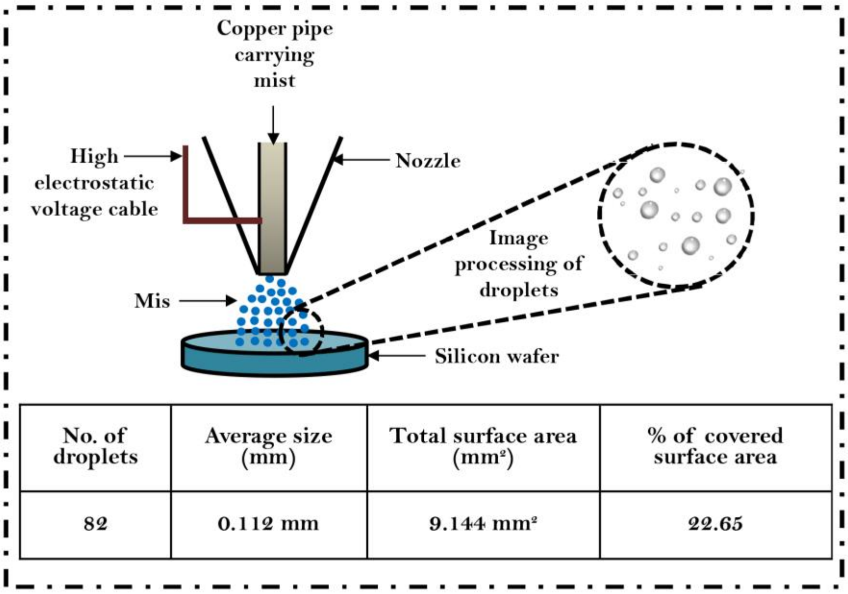


Fig. 4 A schematic of the methodology followed to identify droplet quality

2.2. Droplet Quality measurement

To analyze droplet quality, the generated mist has been sprayed on a silicon wafer with different electrostatic voltage. The droplet quality experiment was repeated twice. Before each experiment, the silicon wafer was thoroughly cleaned by acetone to remove any residues which may affect the experiments. The pressure in FRL unit was allowed to set at 5 bar and then the charged or uncharged spray was allowed to fall onto silicon wafer for 10 minutes at a fixed location of wafer. A constant distance of 20 mm was maintained between the nozzle and silicon wafer, similar to the machining experiments. Microscopic images of the generated droplets were analyzed using image processing to investigate droplet quality in terms of the number of droplets, droplet diameter and surface area covered by droplets, as shown in Fig. 4.

2.3. Friction Test

With the usage of Pin-On-Disk (POD) tribometer, *CoF* between two sliding parts can be evaluated in dynamic conditions. In turning operation also, sliding motion is observed between the tool and workpiece at rake and flank face of cutting tool. So, POD tribometer testing provides the experimental value of *CoF* in a very controlled environment which is difficult to maintain in simulation. So, with the data of *CoF* and wear rate obtained from tribometer testing, one can compare the impact of process parameters, cutting fluid approach and coating of cutting tool without doing actual cutting operation [15,16]. In this view, the *CoF*, wear of pin (in g) and area of worn pin (mm^2) have been measured with Ducom made rotary POD tribometer having model TR-20LE-PHM400-CHM400 (as shown in Fig. 5) to carry out tribotests as per ASTM G99 standard. The 3 mm diameter aluminum pins having 30 mm length and EN31 steel disk which is firmly fixed on spindle have been used for all tribotests. The aluminum pin has been firmly fixed in pin-holder so that it makes a vertical position with the disk for every test. For every test, 100 N normal load and 180 m/min cutting speed have been set by changing the track diameter and rotational speed of disk. The friction tests were allowed to continue for a 3000 m length. After every test, the pin and disk are thoroughly cleaned with acetone to remove the worn particles of pin. The data of *CoF* has been derived from Windcuom software which is interfaced with computer system. The weight loss of aluminum pins has been measured by precision scale having 0.0001 g resolution. The wear marks generated on pins have been analyzed through Mitutoyo made (TM generation B series) optical microscope.

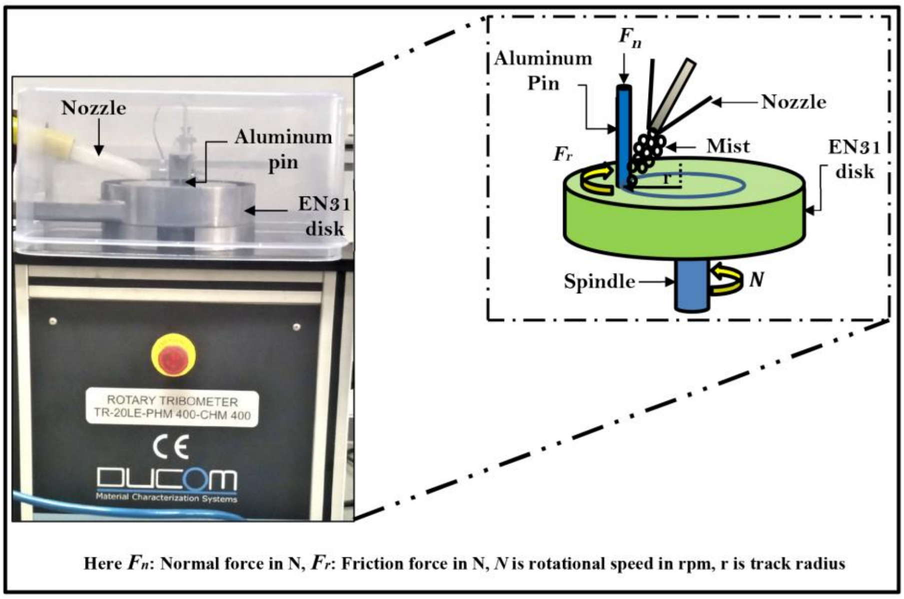


Fig. 5 Setup of pin-on-disk tribometer test with EMQL

2.4. Machining Test

The machining tests are comprised of turning 15-5 PHSS with an 80 mm diameter rod using Kyocera made coated tungsten carbide inserts (CNMG120408MS PR1535, having 0.8 mm nose radius). The cutting speed, feed rate and depth of cut were maintained at 130 m/min, 0.222 mm/rev and 1 mm respectively for two sets of machining experiments. In the first set of experiments, the impact of electrostatic voltage on surface roughness has been investigated by measuring R_a, and tests were repeated twice. The value of R_a includes the impact of all surface profiles covered by the sampling length. So, it is not influenced by drastic changes observed in surface profile. In this context, the surface roughness of machined samples was measured in R_a at five different positions using Taylor and Hobson made a tactile surface profilometer (Surtronic S 128). The sampling, cut-off and evaluation length were kept as 0.8 mm, 0.8 mm and 4 mm respectively as per the ISO 4288-1996 [17]. To minimize the impact of tool wear on surface roughness, a new cutting edge was used for each machining experiment. Following these tests, the optimum voltage based on tribological behaviour explained in 2.3 and surface roughness tests have been used to compare the impact of MQL and EMQL on progressive flank tool wear in the second set of experiments. The progressive flank tool wear has been measured using an optical microscope. The tool wear test was continued until 2400 mm cutting length or one of the following tool life criteria, as per ISO 3685:1993 was arrived [18].

1) Maximum flank wear, $V_{b(max)} \geq 0.6$ mm in case of nonuniform wear form

2) Average flank wear, $V_{b(avg)} \geq 0.3$ mm in case of uniform wear form

3) Sudden failure of cutting edge

3. Results and Discussion

3.1. Droplet quality and tribological performance

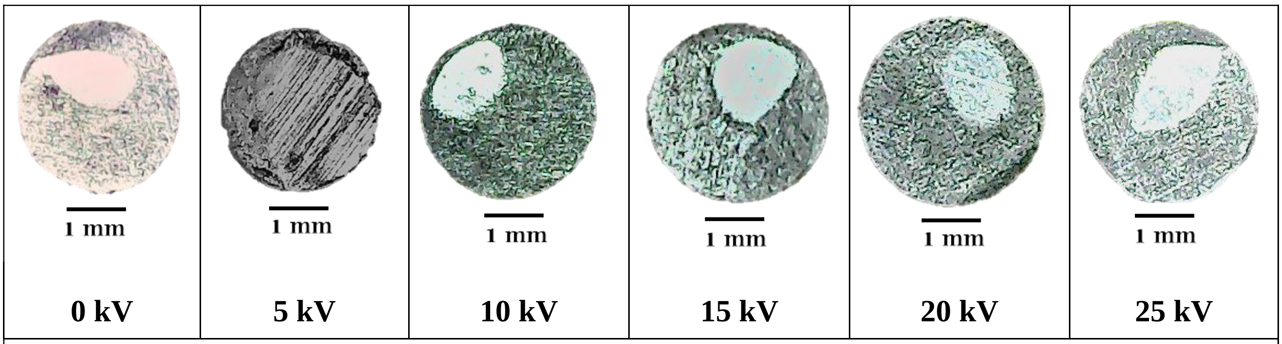
Table 2 shows the results of droplet quality in terms of the number of droplets, average diameter of droplets and surface area covered by droplets. Conventional MQL is defined as 0 V. The investigations demonstrate that the droplet diameter is affected by voltage in EMQL. From Table 2, it can be inferred that the larger number of droplets and surface area covered by droplets with a smaller diameter were generated when EMQL was applied at 20 kV. The better droplet quality observed with EMQL may be due to a reduction in surface tension of charged oil particles. It favors the atomization of droplets, and hence the droplet quality improves [9].

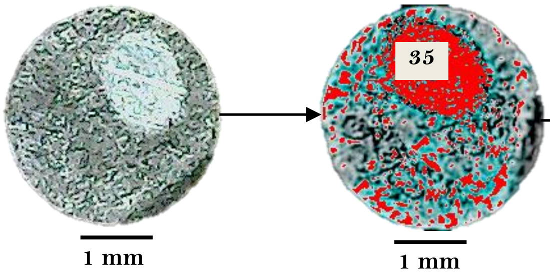
Table 2 Results of droplet quality at a different electrostatic voltage

Electrostatic voltage (kV)	Number of droplets	Average size of droplets in mm	% surface area covered by droplets
0	29	0.123	15.35
5	46	0.137	16.36
10	23	0.125	10.43
15	58	0.141	18.45
20	82	0.112	22.65
25	28	0.177	17.15

The impact of EMQL voltage on tribology behavior has been investigated using a pin-on-disk tribometer. Table 3 shows the wear marks produced on pins due to friction at different electrostatic voltage. A similar methodology used for identifying the droplet quality has been followed to measure the area of wear mark. Table 4 indicates the value of tribological properties at different electrostatic voltage. The lowest results for *CoF*, weight loss of pin (in g) and area of wear mark (mm^2) were observed using EMQL at 20 kV. Exceptionally, a larger area of wear mark was observed with 5 kV. Comparing the results from droplet analysis with that of tribological investigation shows that increasing the voltage from 5 kV to 20 kV effectively improves *CoF*. It can be explained by improved penetrability of finer oil droplets between mating surfaces. This improves the attachment of oil onto the surface, which is then carried into the contact area.

Table 3 Images of wear marks at different electrostatic voltage and methodology to measure the area of wear marks





Sr. No.	Area
35	1.134 **(mm^2)**

Table 4 Results of tribological performance at a different electrostatic voltage

Parameter	Voltage (kV)					
	0	**5**	**10**	**15**	**20**	**25**
CoF	0.076	0.044	0.042	0.037	0.027	0.038
Weight loss in pin (g)	0.0054	0.0101	0.0046	0.0051	0.0039	0.0055
Area of wear mark (mm^2)	1.351	3.82	1.286	1.37	1.134	1.573

It is reported that, if the electrostatic voltage is increased beyond a specific limit, then it reduces the formation of metallic oxide which helps to promote lubrication layer [9]. Moreover, the reaction of charged oil particles with sliding surfaces increases the contact area by generating soft surfaces resulting in increased friction force [19]. It may be one reason for not observing better tribological and droplet properties at 25 kV as compared to 20 kV electrostatic voltage.

3.2. Surface roughness machining tests

A series of machining tests have been conducted to evaluate the impact of electrostatic voltage on surface roughness (R_a) in machining 15-5 PHSS using a coated carbide tool.

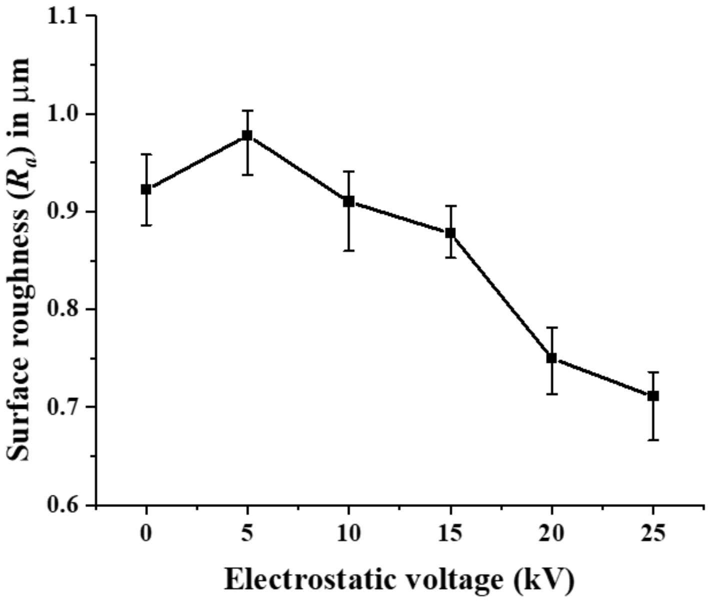


Fig. 6 Variation in surface roughness (R_a) with a change in electrostatic voltage

From Fig. 6, it is observed that the comparable lower value of surface roughness (R_a) was found at 20 and 25 kV. This result confirms the better performance of EMQL especially at higher electrostatic voltage as compared to MQL. However, a higher value of R_a observed at low electrostatic voltage is attributed to the domination of surface irregularities hindering intimate contact of charged oil particles with tool and workpiece surface [20]. So, the effectiveness of MQL in terms of lubrication is depressed and hence higher surface roughness is found.

3.3. Progressive tool wear investigation

Based on the investigations reported in 3.2, EMQL performs best at 20-25 kV. Specifically, 20 kV resulted in the best performance regarding droplet generation and tribological behavior. Therefore, machining tests for progressive tool wear were conducted using 20 kV for EMQL following the condition and machining parameters explained in 2.4. The flank tool wear progression was measured during machining experiments. Fig. 7 shows the variation in tool wear with the change in cutting length for MQL and EMQL machining techniques. The cutting tool used for MQL and EMQL reached 0.127 mm and 0.078 mm flank wear respectively after machining 2400 mm cutting length. This indicates a decrement of 38% in tool wear in case of EMQL at 20 kV as compared with conventional MQL.

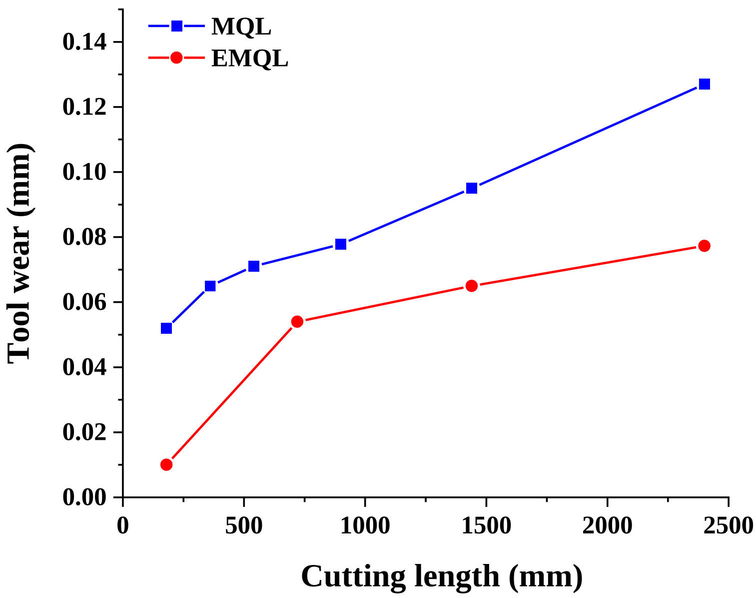


Fig. 7 Comparison of tool wear in MQL and EMQL with a change in cutting length

Fig. 8 (a) and (b) show images of flank wear produced on the tools used for MQL and EMQL machining tests at the end of each experiment respectively. Flank wear due to abrasion was the dominant tool wear mechanism for both experiments. However, adhesion and built-up formation were also noticed specifically in the MQL experiment.

The improved wettability and penetrability of charged particles are noticed in EMQL technique as compared to near to dry machining. It is also reported that finer droplets increase heat removal from the cutting zone by enhancing adsorption film formed at the tool-chip interface [9]. Based on the analysis, oil droplets with smaller diameter were generated at 20 kV, which can potentially raise heat removal. Besides, smaller droplets can penetrate the gaps between cutting tool and workpiece, and provide improved lubrication. Moreover, it is observed that EMQL results in the generation of a metallic oxide layer which positively alters frictional behavior at the cutting zone. The abundant amount of O_2 available in atmosphere forms radical $\dot{O}$ reacting with charged particles. These energized $\dot{O}$ can easily react with workpiece surface and forms a layer of ferrous oxide (FeO). Further reaction of FeO with $\dot{O}$ generates a thin layer of ferric oxide (Fe_2O_3) on workpiece [9]. It has been reported that brittle metallic oxides work as a lubricant layer between sliding surfaces which increases wear resistance and anti-scuffing properties [21].

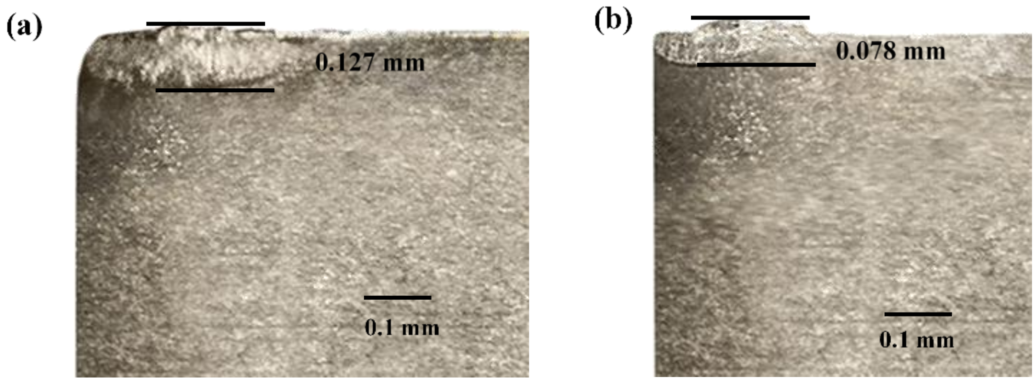


Fig. 8 Image of flank tool wear occurred during **(a)** MQL and **(b)** EMQL

Improved lubrication reduced heat generation occurred owing to friction at cutting zone. This can lead to better machining performance in terms of lower tool wear and surface roughness produced with EMQL in comparison with MQL machining.

4. Conclusions and future work

A new electrostatic MQL (EMQL) setup has been presented by delivering vegetable oil through a copper tube inside an MQL nozzle connected to a high voltage source. The novel process described in this paper demonstrated that machining performance can be significantly improved by charging oil droplets in MQL. From the results, it is concluded that the electrostatic voltage certainly improves droplet quality in terms of the number of droplets, diameter of droplets and surface area covered by droplets. Improved performance in terms of tribological properties and machining has been observed at 20 kV electrostatic voltage. The flank tool wear for MQL and EMQL machining reached 0.127 mm and 0.078 mm correspondingly after machining 2400 mm cutting length. This shows a 38% lower tool wear in case of EMQL at 20 kV in comparison with traditional MQL. The superior performance observed in EMQL technology is due to ultra-high electrostatic charged mist particles which improve droplet quality and penetrability into the cutting zone. In the future, the impact of voltage on cutting forces, power consumption and tool life will be analyzed by considering different material pairs, process parameters, and cutting oil.

Acknowledgments

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