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MQL assisted cleaner machining using PVD TiAlN coated carbide insert: Comparative assessment

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Minimum quantity lubrication (MQL) is an alternative over dry machining due to economic and ecological sustainability. In the current research, a comparative investigation has been carried out on machinability and surface integrity aspects of hardened AISI 4340 steel using PVD TiAlN coated carbide inserts during dry and MQL assisted hard turning. Under the dry condition, turned surface has been encountered tensile residual stress whereas compressive residual stress has been generated under MQL condition. Formation of a white layer on the chip has not been experienced under both conditions. Cutting speed predominantly influences tool wear and feed influences more on surface roughness. Dimensional deviation and auxiliary flank wear have been significantly reduced under MQL condition with 16.21% cost savings. An improvement in machinability characteristics and surface integrity under MQL cutting has been noticed compared to dry with favorable interaction and contribute towards cleaner machining process. This may be adopted in machining shop floor as a good replacement over dry machining.

Keywords: MQL, Surface integrity, Machinability, Tool wear, Residual stress, Surface roughness

1 Introduction

Ecological, work-related health threats and the influence of worldwide climate amendment are of growing anxieties of the 21st century and especially these concerns have recently led to the setting up of strict government guidelines and mandates for worldwide metal machining industries[1]. Dry machining is nature-friendly and attributes no hazards towards machine operator health but it declines the productivity and quality of finished product particularly in the case of hardened materials, a similar finding was reported[1]. Metal working lubricants actively worked as an important role in cooling and lubrication of the metal machining surrounding since few decades. Recently, minimum quantity lubrication (MQL) emerged as a novel technique to achieve cleaner metal machining. In comparison with flood cooling, MQL utilizes only a few millimeters/hr of lubricating liquid in the form of atomized fine droplets. Despite being economical and eco-friendly, MQL provides improved behavior of tool wear and surface finish in machining[1,2].

The optimum parametric range during graphite based nanofluid MQL (NFMQL) assisted turning of titanium alloy are found to be lower range of cutting speed and feed and moderate value of approach angle using TOPSIS and PSO method[3]. The MQL based vegetable oil attributes superior lubrication effect relative to mineral oil and flood lubrication due to the high binding energy and low friction coefficient[4]. During turning of AISI 4340 steel, MQL exhibited the superior performance over flooded cooling surrounding and reduced the machining zone temperature and improved the chip tool interaction thus, around 7 to 10 % improvement in surface quality was observed[5,6]. When compared the machining performances of MQL (with menthol), dry and wet environments, lower tool wear and improved surface quality are found under MQL relative to wet and dry environments[7].

Residual stresses generated on to the machined surface may change the material properties like fatigue life, surface quality and surface hardness. Increment in input variable like speed, feed and nose radius of tool contributes to additional tensile residual stresses[8]. A precise combination of machining variables minimizes residual stresses evolved in dry and MQL environments or can match with emulsion assisted machining[9]. Residual stresses acting on the machined surface are directly related to temperature generated during machining[10]. Residual stresses and surface finish were primarily inflated by feed and cutting speed whereas it can be lowered by proper selection of cutting insert geometry[11]. Growth in tool

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nose makes the surface residual stresses more tensile in nature[12]. Feed is predominant factor for compressive residual stresses and it can be controlled by choosing appropriate feed and rake angle[13]. Cutting speed-feed primarily affected the residual stresses and also improved the strain rate and cutting force, resulting in the generation of larger compressive stress[14]. Tensile residual stresses produced on the superficial upper machined surface while compressive residual stresses on subsurface or underneath the surface. Residual stresses mostly influenced by pre-stress load and tool nose condition[13,15]. Compressive residual stresses generated under the surface when working with fresh cutting insert while tensile residual stresses occurred at the upper surface of the workpiece when using worn out cutting inserts[16].

White layer formation during hard machining affects the tool life, surface quality, residual stresses etc. Thus understanding the reason behind white layer formation is a vital aspect in hard machining. Cutting feed directly influenced the thickness of a white layer but higher cutting speed machining declined the thickness of white layer due to the very short contact time available between tool and workpiece[17]. White layer formation in any manufacturing process is governed by three foremost mechanisms (a) phase transformation as a result of immediate heating followed by a subsequent cooling, (b) plastic deformation ensuring fine grain structure, and (c) chemical surface reaction with the surroundings[18]. Compressive residual stresses decrease with white layer thickness[19]. Change in the microstructure of surface after machining may be attributed to white layer generation. Initial hardness, the shape of insert and input variables influences the white layer thickness. The thermal effect also causes of white layer formation due to rapid heating and cooling on the machined surface which results in martensitic structure development[20].

Study of the microstructure of AISI 4340 heat treated steel is very essential as it finds its application in various fields like aerospace, automobile etc. Decomposition of retained austenite typically started at temperature range of 200 to 300 $^{\circ}$C. At 250 $^{\circ}$C, the precipitation of rod-like cementite initiates and alters into spheroid[21] shape at 400 $^{\circ}$C. Tempering at a high temperature brings alteration in lathe martensite and at elevated temperature tempering the elongated packet-lath morphology of martensite is retained up to extended period[22]. In the cutting process, assorted types of carbide precipitate formed at the machined surface due to diverse tempering temperature generated. Consequently, inter-lathe austenite was retained on to the surface which attributes declined the toughness[23]. Primary influencing aspect on wear is the presence of various carbides in the microstructure of steel. The abrasive action by these hard carbides resulted in the generation of grooves along the wear zone[24]. Nanofluids application in MQL machining of titanium alloys for surface roughness was studied and optimized the parameters. RSM model using Box-Cox transformation predicted well[25].

From the past kind of literature available, it is observed that the tool life and surface integrity was affected largely due to higher heat generation in hard turning. Dry as well as conventional cooling in hard machining is usually restricted because of high cutting force, tool wear and more important higher thermal stresses. However, in recent years, MQL emerged as an economic and efficient lubrication technique. Varieties of liquids have been utilized so far to get the hazard free environment along with higher machinability. Keeping this view, the present study utilizes industry based LRT 30 (iron-aluminium) oil through MQL which is rarely investigated by the previous researcher. Also, very rare pieces of literature included the study on the influence of MQL on various surface integrity aspects like a change in the microstructure, development of residual stresses (compressive and tensile), surface topology, white layer formation and chip morphology. Also, the effects of residual stresses on flank wear and surface roughness are rarely reported and thus required to be extensively explored during machining of hardened steel using coated carbide inserts. Thus, current study investigates extensively on various surface integrity and machinability characteristics such as tool wear, tool life, surface roughness and its topography, residual stresses, white layer formation, microstructure change, chip morphology, dimensional deviation, modeling and economical aspects on hardened AISI grade 4340 steel under dry and MQL environments utilizing PVD TiAlN coated carbide inserts.

2 Experimental Procedure and Characterization Results

Hard turning experiment has been carried out based on experimental design through CNC (Fanuc controller) lathe under dry and minimum quantity lubrication (MQL) environments. The experimental approach is shown in Fig. 1. Table 1 displayed the detail of experimentation and input cutting parameters along with their levels. A cylindrical solid rod of AISI 4340 grade (50 ±1 HRC) steel having 40 mm diameter and 180 mm length were used as a workpiece. PVD multilayer coated (TiAlN) TN 6010 carbide cutting insert was used having ISO configuration CNMG120408 and clamped on right hand tool holder (PCLNR2525M12) having a geometry of rake angle -6°, clearance angle 6° and approach angle 95°, respectively. Flank wear measurements have been carried out by an optical microscope with an image analyzer (Olympus microscope, STM 6) and taken as criteria of 0.2 mm (Dosbaeva *et al.*[26]) of flank width. SEM and EDS of the tooltip before and after machining and white layer analysis have been analyzed with HITACHI make SU3500 Scanning Electron Microscope with INCA

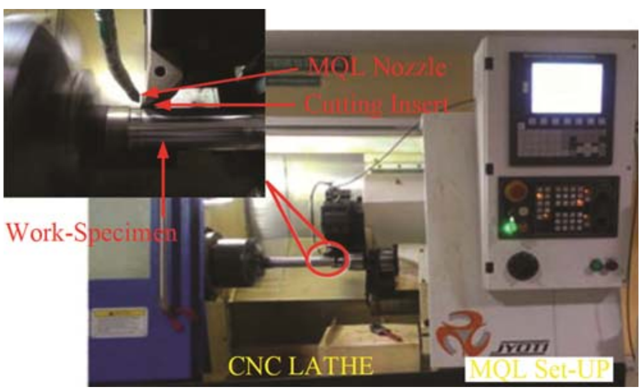

Fig. 1 — Experimental set-up.

Table 1 — Experimental particulars and cutting conditions.

Test cutting conditions	Descriptions
Machine tool	CNC lathe (Fanuq operating system)
Test specimen	AISI 4340 steel rod
Hardness	50±1 HRC
Test specimen dimension	Diameter-40mm and length-180mm
Cutting inserts	CNMG120408 (WIDIA) (PVD TiAlN coated) (TN6010)
Tool holder	PCLNR2525M12
Cutting speed (m/min)	50, 100, 150, 200
Feed rate (mm/rev)	0.04, 0.08, 0.12, 0.16
Depth of cut (mm)	0.1, 0.3, 0.4
Cutting environment	Dry and MQL
Lubricant	LRT 30 (DROPSA)
MQL parameters	Air pressure (5bar) Lubricant flow rate (50 ml/hr)

software by OXFORD Instruments act model make energy dispersive spectroscopy system. Taylor Hobson (surtronic 25) tester was used for measurement of average surface roughness (Ra) with criterion of 1.6µm comparable with grinding. X-ray diffraction method based on goniometry used for measuring the residual stress of the turned workpiece with PROTO iXRD instrument consisting of MG40 goniometer with 40 mm focal distance and the standard 30 mm X-ray tube which utilizes Cr_K-Alpha. Microhardness test has been accomplished using Vickers tester (Zwick/Roell, ZHV30) with a diamond indenter and 1 kg load (HV1). Microstructure study was carried out by Leica Inverted microscope (Leica Microsystems, DMI 3000M) with 500X magnification.

For estimating the standard experimental error of flank wear and surface roughness, the repeat-ability check has been carried five times at process parameters (v = 50 m/min, f = 0.04 mm/rev and d = 0.1 mm) and found to be error range of ± 2%. Similarly, for all data set measurement, errors for responses were calculated under dry and MQL and the standard error noticed to be below than ± 1%. Chemical composition test of work specimen performed through Spectromax and found in % of weight i.e. 0.380C, 0.307Si, 0.890Mn, 0.039P, 0.011S, 0.900Cr, 0.103Ni, 0.019Cu, Fe balance.

DROPSA (Italy) equipment has been used as minimum quantity lubrication set up with the VIP5 controller unit and connected to an air compressor. Iron-Aluminium lubricant (LRT 30) used as cutting fluid mixed with air and then sprayed at the cutting zone. The oil ejected with 5 bar pressure and spraying at the rate of 50 ml/hr at the machining zone. LRT 30 lubricant has the properties like environment friendly, non-toxic and insoluble in water etc. The viscosity of LRT 30 iron aluminium oil at 40 °C is 24 centistokes, specific weight at 15 °C is 0.900 kg/L and flammability point is greater than 220 °C. The MQL set up and its flow mechanism is illustrated in Fig. 2. Compressed air from the air compressor is supplied to the air solenoid valve. Then, controlled compressed air from the solenoid valve goes into the oil flow control valve and moisture control valve. The moisture constituent in the air is entirely removed by the moisture control valve and then it is supplied to the mixing chamber. In the mixing chamber, moisture free air and LRT 30 oil have been mixed appropriately and then supplied into the cutting zone with a spray nozzle (CH10 5/16). The experimental results are shown in Table 2.

Abrasion test of PVD TiAlN multilayer coated carbide insert has been performed involving dry sand rubber wheel (ASTM-G65) illustrated in Fig. 3 using DUCOM, dry abrasion tester (TR-50) using quartz sand particle AFS 50/70 with a load of 49 N, test duration of 5 min and a rotational speed of rubber wheel is 200 rpm. The results reveal that the abrasion wear rate of (PVD TiAlN) coated carbide insert is 0.00024 gm/min which confirms the higher abrasive resistance of cutting insert. Micro hardness (HV) of cutting insert has been carried out two times with 1 kg load (HV1) by Vickers micro-hardness tester (Zwick/Roell, ZHV30) through diamond indenter and found to be 1792 HV.

Table 2 — Experimental results under dry and MQL conditions.

Run No.	Depth of cut (*d*), mm	Feed (*f*), mm/rev	Cutting speed (*v*), m/min	Dry environment		MQL environment	
				VBc (mm)	Ra (μm)	VBc (mm)	Ra (μm)
1	0.1	0.04	50	0.068	0.36	0.041	0.27
2	0.1	0.08	100	0.079	0.42	0.057	0.32
3	0.1	0.12	150	0.098	0.62	0.072	0.54
4	0.1	0.16	200	0.122	1.00	0.092	0.88
5	0.3	0.04	150	0.111	0.52	0.069	0.41
6	0.3	0.08	200	0.171	0.56	0.084	0.82
7	0.3	0.12	50	0.077	0.69	0.062	0.67
8	0.3	0.16	100	0.071	1.01	0.063	0.61
9	0.4	0.04	200	0.221	0.70	0.097	0.62
10	0.4	0.08	150	0.115	0.42	0.080	0.55
11	0.4	0.12	100	0.078	0.48	0.069	0.6
12	0.4	0.16	50	0.092	0.90	0.073	0.72

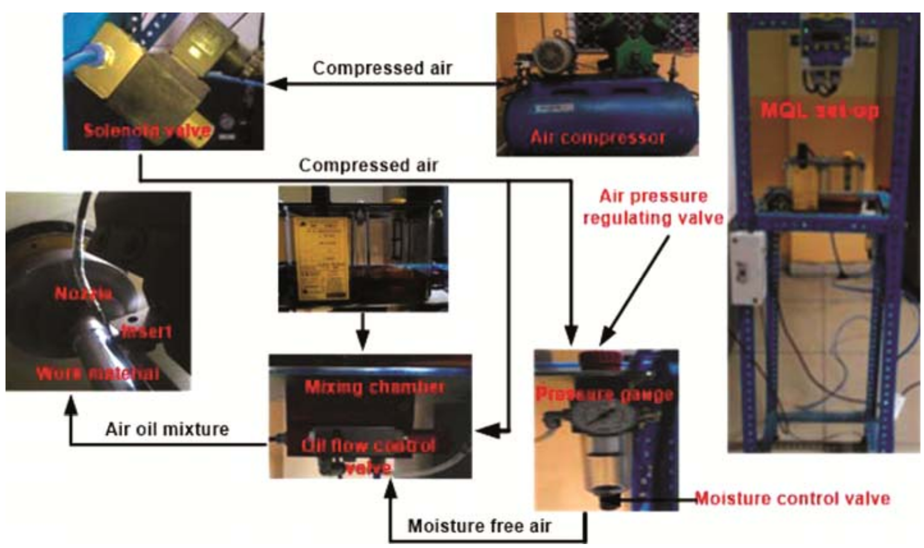

Fig. 2 — MQL set-up and flow mechanism.

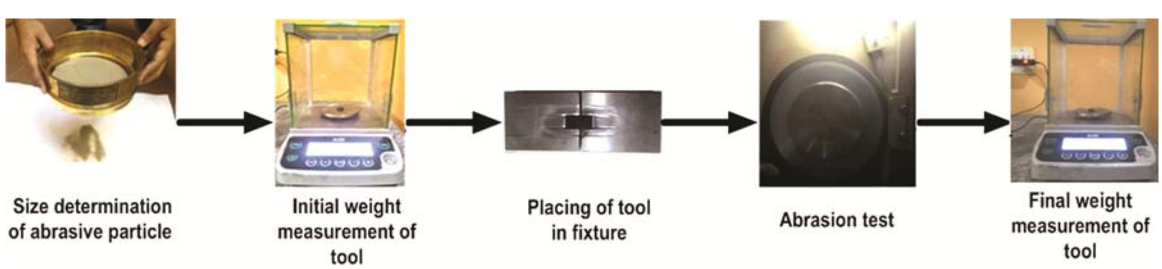

Fig. 3 — Presentation of abrasion test process.

3 Results and Discussion

3.1 Residual stress analysis under dry and MQL

Residual stress measurement in hard turning of AISI 4340 steel under dry and MQL condition was performed at Run 4 in the axial direction. Tensile residual stress (+71.6 ± 9.8 MPa) were recorded under dry conditions whereas in MQL, compressive residual stress (-89.3 ± 8.2 MPa) are obtained shown in Fig. 4. In dry machining condition due to high tool wear rate and temperature, the residual stresses on the external surface tend to be tensile in nature. Thus both mechanical and thermal effects under dry condition act in generating tensile residual stress (Saini *et al.*[11]; Liu *et al.*[12]; Jomaa *et al.*[14]). But machining under MQL assisted condition, lower tool wear rate was observed due to minimal thermo-mechanical effects on the tool tip that tends the residual stresses to be compressive in nature. In other words, MQL enhances penetration of lubricant droplets into the cutting zone that provides improved heat reduction compared to dry cutting[27,28].

Residual stress has a significant impact on flank wear under both dry and MQL assisted hard turning. High tensile residual stress and higher flank wear (0.122 mm) experienced under dry condition and may be attributed due to the higher cutting force involved in hard machining that leads to severe plastic deformation as well as the effect of higher cutting temperature. So, the combined effect of severe plastic deformation (mechanical) and increase in temperature (thermal) enhances the flank wear of the cutting tool under dry circumstances[13,14]). This gives rise to surface degradation phenomena like material side flow, the formation of ridges and non-uniform surface and leads to increment in surface roughness. However, thermo-mechanical effects on the tool tip drastically reduced under MQL condition and consequently, lower tool wear rate (0.092 mm) was observed under MQL condition.

3.2 Microstructure and surface topology study under dry and MQL

Microstructure study has been carried out for heat treated AISI 4340 steel samples prior to and post machining (Run 4) which are presented in Fig. 5. A significant alteration in microstructure has been observed after machining the steel samples (Fig. 5a and 5b). In the un-machined sample, martensite, ferrite and carbide structure were observed. Presence of hard carbide particle in the test sample is observed which are solely responsible for tool wear due to abrasion[24]. Noticeable changes in the microstructure of test sample were noticed as a result of heat generation during hard machining under both dry and MQL environment. This heat facilitates tempering the martensite which splits into ferrite and cementite forming a complex structure known as tempered martensite. Generally tempering process in carbon steels alters the shape and distribution of carbides, where the breakdown of retained austenite usually starts. Precipitation of cementite takes place and takes the shapes of plate or spheroids like structure in dry cutting due to high temperature. However, MQL assisted turning reduces the temperature compared to dry where precipitation of cementite takes place and takes shapes of lathe or needle-like finer structure[22,23].

Surface topology is predicted by the maximal and minimal gap between the two consecutive groves lines produce upon the machined surface as a sign of cutting feed. Fig. 6 represents the surface topology of the machined surface at different experimental runs (Run 1-Run 4) under dry and MQL with a variation of feed rate from 0.04 mm/rev to 0.16 mm/rev. Turning with the highest feed will bring out more extensive

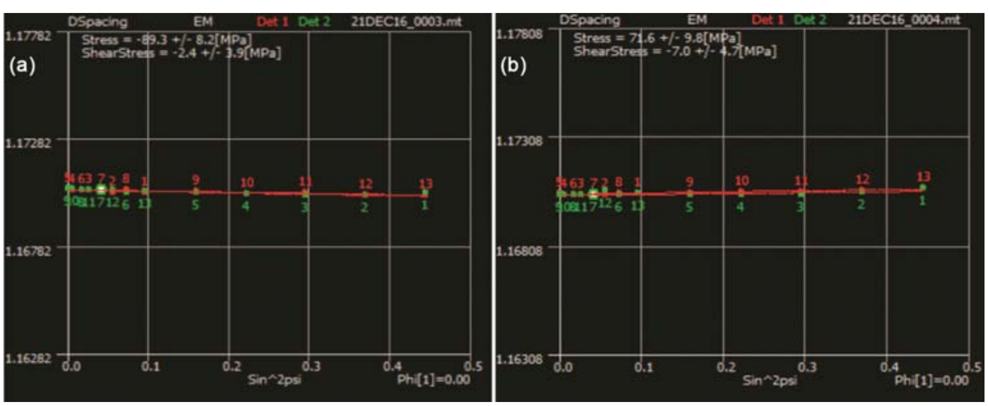

Fig. 4 — Graph illustrating residual stresses under different machining conditions (a) MQL (run 4) and (b) Dry conditions (run 4).

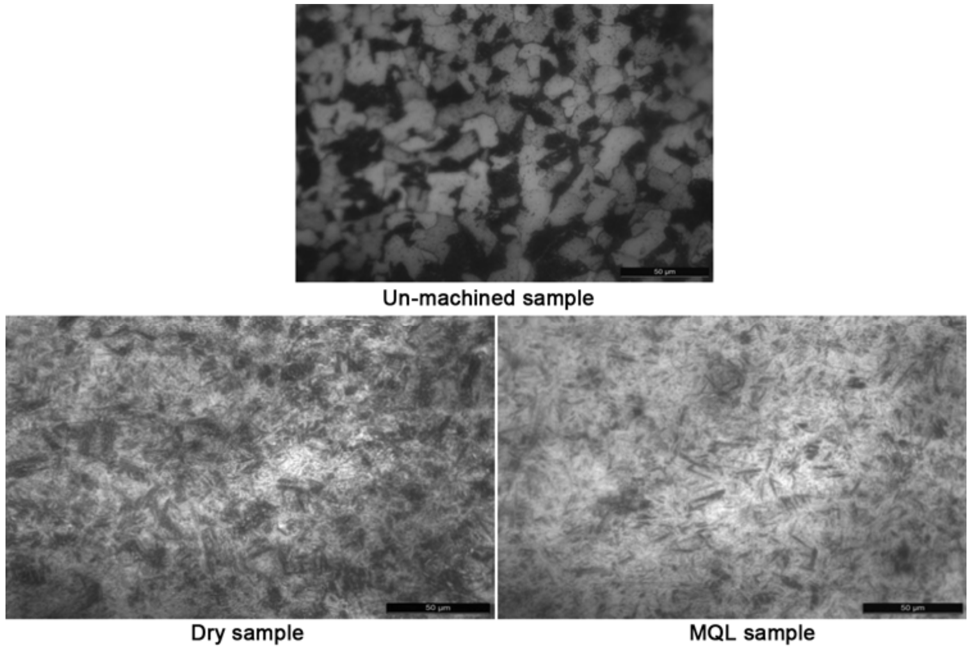

Fig. 5 — Optical image of microstructure (a) un-machined surface (b) Surface obtained under dry (run 4) and (c) Surface obtained under MQL (run 4).

groove lines with higher surface roughness values while fine groove lines are noticed with lower feed value as evident from Fig. 6a-Fig. 6d with lower surface roughness values. Under MQL assisted hard turning, extremely compressed air-oil mixed coolant reduces the frictional force and contact stress, which reduces the cutting force resulting in finer groove lines (Fig. 6f) as contrasted with dry state machining (Zou *et al*.[29]). Thus enhanced surface finish was observed under MQL assisted machining without the formation of ridges whereas in dry condition, ridges (Fig. 6d) were noticed at maximum feed-speed condition (run 4). Reduction in contact stress and frictional force at the insert-job boundary is archived by a decline in cutting force and as an outcome enhanced surface finish is noticed owing to decline in the impact of plastic deformation of the machined surface. Mechanism of plastic deformation results in material side flow (Fig. 6a) and ridges (Fig. 6d) on the machined surface. Feed marks and feed mark area expansion of ridges was noticed[30]. Worn out the edge of the insert is the sole reason of tool wear which is the cause of ridge formation.

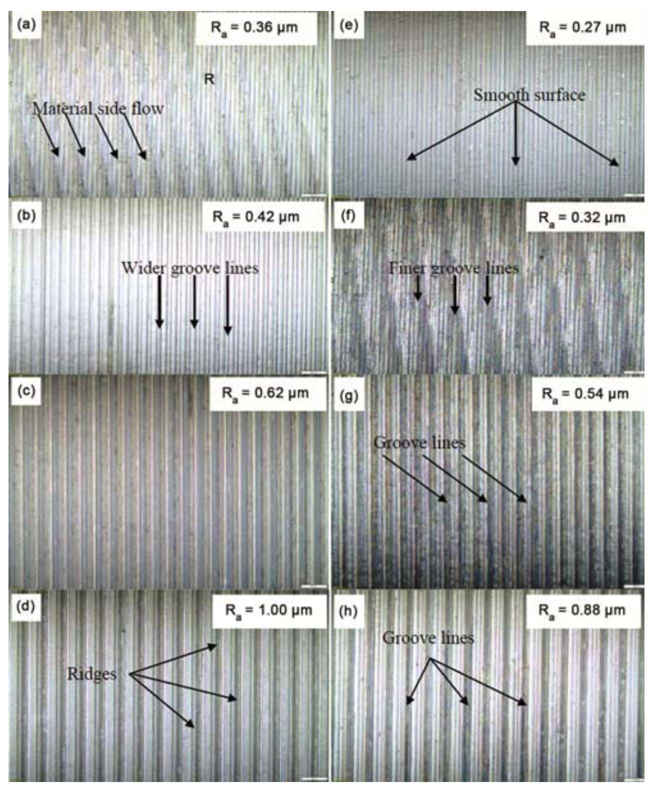

Fig. 6 — Surface topology of machined surface under (a-d**)** Dry (run 1-4) and (e-h**)** MQL (run 1-4).

3.3 Surface roughness and tool wear investigation under dry and MQL

Surface roughness values in dry and MQL machining conditions are within the limiting criteria of 1.6 microns (Table 2). However, in the majority of runs under MQL condition, surface roughness values are less compared to dry machining[7]. Surface roughness increases with feed rate as observed in run

Table 3 — ANOVA for Ra (MQL).

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Contribution %	Remarks
d	2	0.04006	0.04006	0.02003	22.26	0.016	10.73	Significant
f	3	0.14042	0.18236	0.06078	67.54	0.003	37.63	Significant
v	3	0.18990	0.18990	0.06330	70.33	0.003	50.89	Significant
Error	3	0.00270	0.00270	0.00090			0.75	
Total	11	0.37309						

S = 0.03 R^2 = 99.28% R^2(adj) = 97.35%

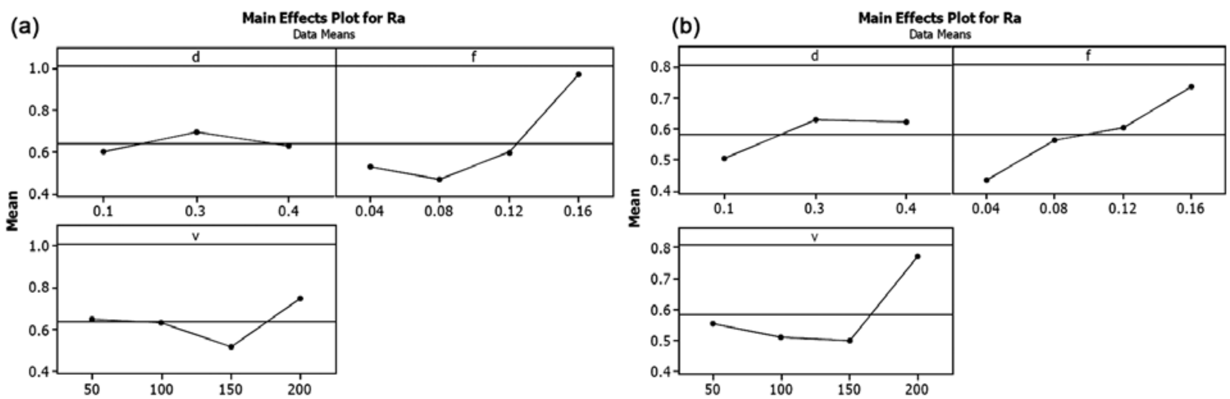

Fig. 7 — Main effects plot for surface roughness (a) dry (b) MQL.

no. 4, 8, 12 and 16 respectively from Table 2, similar observation were reported by[31,32]). MQL assisted cooling provides better lubricant droplets penetration into the cutting area and results in advanced performance to that of the dry cutting environment. Due to highly compressed oil mist, higher curling of the chip was feasible that minimizes the contact length and resulted in better surface finish. Additionally, broad chips are the consequence of the side flow that can create lower surface quality for dry machining. Feed rate and cutting speed are the most dominating machining parameter for the growth of surface roughness[33,34]) as evident from main effect plot (Fig. 7) and ANOVA study (Table 3). In the analysis of tool wear under dry and MQL environment, abrasion was noticed to be the key mechanism governing the wear at flank surface[35] and flank wear values are well within criterion of 0.2 mm except at Run no. 9 (v = 200 m/min, d = 0.4 mm and f = 0.04 mm/rev) at dry condition as observed from Table 2. MQL assisted hard turning outperforms over dry conditions in lowering flank wear as seen from Table 2. Severe abrasion was noticed at run 4 (Fig. 8d and Fig. 9a) under dry condition due to the increase of friction and plastic deformation and rise of temperature. In MQL cooling condition, both convection and evaporative heat transfer mechanisms were active where microdroplates of lubricants with high pressure penetrate in the cutting zone and facilitate transfer of heat due to higher heat transfer coefficient of the oil mist[15,36]. Consequently, a thermo-mechanical force on the tool reduces and lowers tool wear. Elemental analysis of cutting insert before and after (dry and MQL) machining for run 4 is listed in Table 4. After machining percentage of C (by weight or by atom) increases under both machining condition but in dry condition amount of improvement is more indicating diffusion of carbon content from the workpiece to tool tip and is more sensitive under dry condition compared to MQL. Also, after machining, % of Titanium (Ti) reduces in dry as well as in MQL condition and iron content has been noticed due to adhesion and diffusion. SEM image and EDS graph show the elemental content of the cutting insert at Run 4 (Fig. 10). Machining insert has performed well under MQL environment in comparison to dry[37]. From the main effect plot (Fig. 11) and ANOVA (Table 5) of flank wear under dry and MQL condition, the most dominating parameter for the growth of flank wear is the cutting speed as p value is less than 0.05 at 95% confidence level.

3.4 Chip morphology and white layer generation under dry and MQL

The chip formation in hard machining is attributed towards the initiation of crack and slip. Helical and ribbon chip in terms of shape whereas metallic, metallic blue and blue chips in terms of colour were noticed in this present experimental study. The appearance of saw-tooth and serration was observed on the chip surface illustrated in the SEM image of Fig. 12 at Run 4[38,39]. Blue colour chip was observed in maximum run under dry condition (Fig. 13 and Table 6)

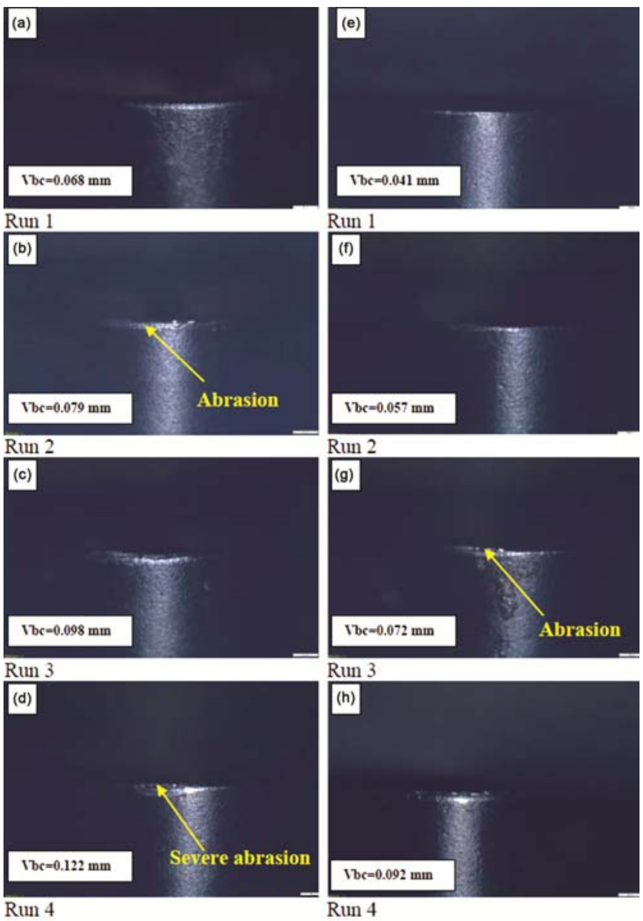

Fig. 8 — Optical image of flank wear (a-d**)** dry (e-h**)** MQL.

which can be the reason for the increase of temperature at the chip-tool interface. Investigation of chip morphology reveals that serration had occurred on the free (upper) surface of chip relating side flow and shear crack as a result of plastic deformation of chips and rise of temperature. Application of MQL lowers the cutting temperature, which results in the occurrence of metallic colour chips in maximum test runs. Similar findings have been reported by Sharma *et al.*[40]. Formation of white layer takes place due to initiation of the mechanical or thermal phenomenon. White layer formation attributes to fast heating above the austenite temperature (thermally) or because of rigorous plastic deformation[21] (mechanically). In the present investigation, no white layer formation was observed under both dry and MQL circumstances at similar parametric setting at Run 4 (Fig. 12). As a result, the lower rate of tool wear is observed due to the superior performance of TiAlN coating on carbide substrate. Lower flank wear reduces the contact length among the flank face of the insert and a work-specimen surface which do not alter the content of retained austenite and avoids the formation of the white layer under dry condition[18,41]). Reduction in temperature under MQL keeps the insert coating intact for a longer time resulting in lowering flank wear and elimination of severe plastic deformation without formation of the white layer.

3.5 Empirical modeling

Modeling of responses has been carried out through regression methodology with R-square value for correlations. The significance of model and close correlations with experimental data is obtained when R-square value near to 1 (100 %). The modeling has been carried for output responses such as wear at flank face (VBc) and average roughness of turned surface (Ra) which are presented in Eqs.

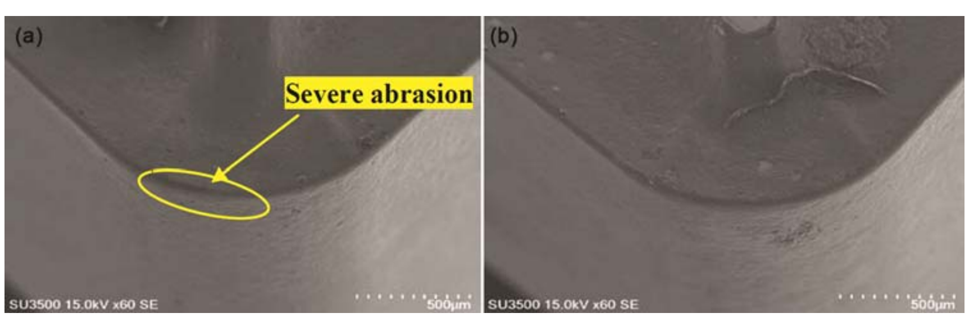

Fig. 9 — Tool tip SEM image at run 4 (v = 200 m/min; f = 0.16 mm/rev; d = 0.1 mm) (a**)** dry and (b**)** MQL.

Table 4 — Elemental details of cutting insert prior and post machining at v = 200 m/min; f = 0.16 mm/rev; d = 0.1 mm.

Un-machined			Used in Dry cutting			Used in MQL		
Element	Weight %	Atomic%	Element	Weight %	Atomic%	Element	Weight %	Atomic%
C K	8.29	15.30	C K	14.44	22.23	C K	9.87	15.34
N K	26.35	41.70	N K	20.29	26.77	N K	21.70	28.93
O k	6.11	8.46	O K	28.30	32.70	O K	31.53	36.80
Al K	19.81	16.28	Al K	14.04	9.62	Al K	15.84	10.96
Ti k	39.45	18.26	Ti k	20.00	7.72	Ti k	16.60	6.47
Total	100		Fe K	2.91	0.96	Mn K	0.69	0.24
			Total	100		Fe K	3.76	1.26
						Total	100	

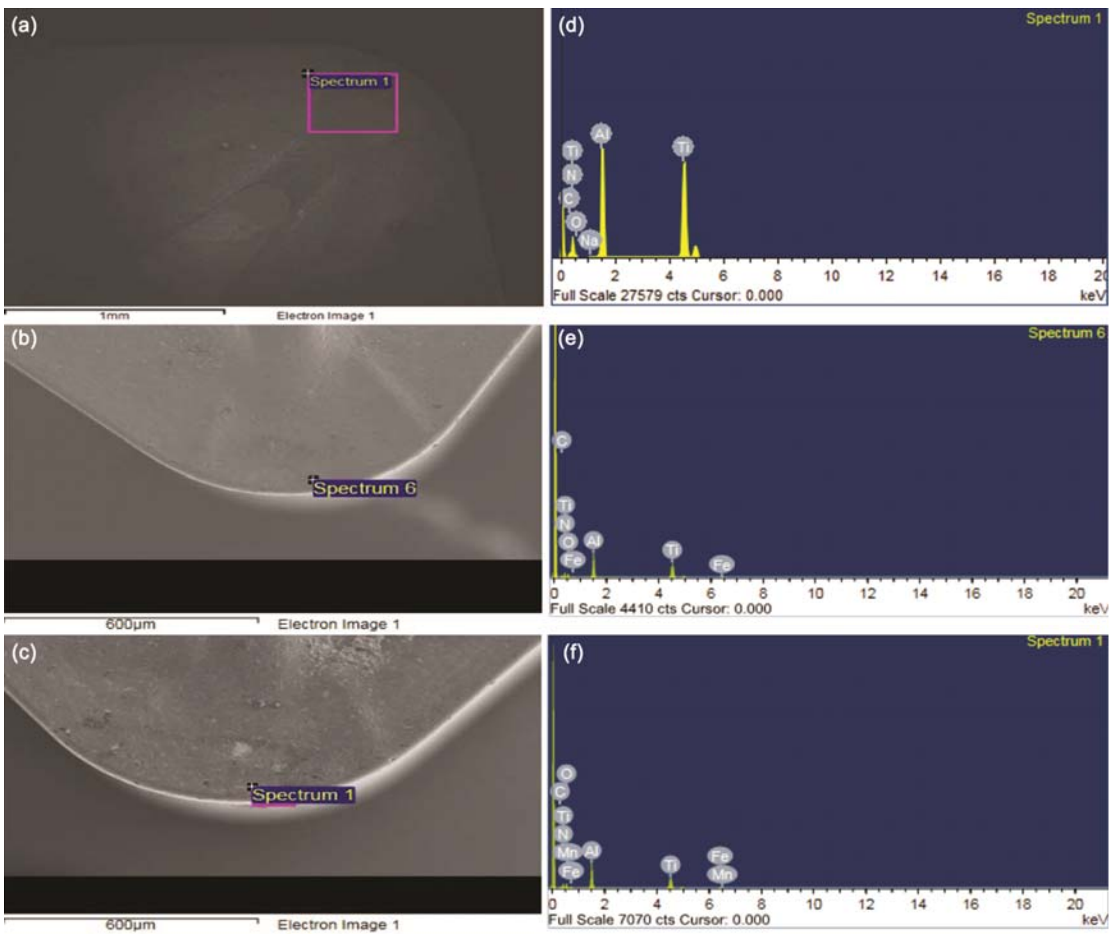

Fig. 10 — SEM and EDS image (a & d) for un-machined, (b & f) dry and (c & f) MQL conditions at run 4 (v = 200 m/min; f = 0.16 mm/rev; d = 0.1 mm).

Dry condition

$$VBc = 0.097187 - 0.403750\ d + 0.913750\ f - 0.000783\ v + 0.593750\ d^2 + 0.039062\ f^2 + 0.000007\ v^2 - 0.556250\ df + 0.001335\ dv - 0.006688\ fv,\ R^2 = 99.93\%;\ R^2\ (adj) = 99.6\% \quad \ldots (1)$$

$$Ra = 0.336200 + 1.650000\ d - 1.250000\ f - 0.002400\ v - 3.125000\ d^2 + 61.718700\ f^2 + 0.000000\ v^2 - 13.12500 df + 0.007300\ dv - 0.023700 fv,\ R^2 = 99.98\%;\ R^2\ (adj) = 99.90\ \% \quad \ldots (2)$$

MQL condition

$$VBc = 0.026938 - 0.015417\ d + 0.382500\ f - 0.000018\ v + 0.310417\ d^2 - 0.117187\ f^2 + 0.000001\ v^2 - 0.712500\ df - 0.000310\ dv - 0.001063 fv,$$

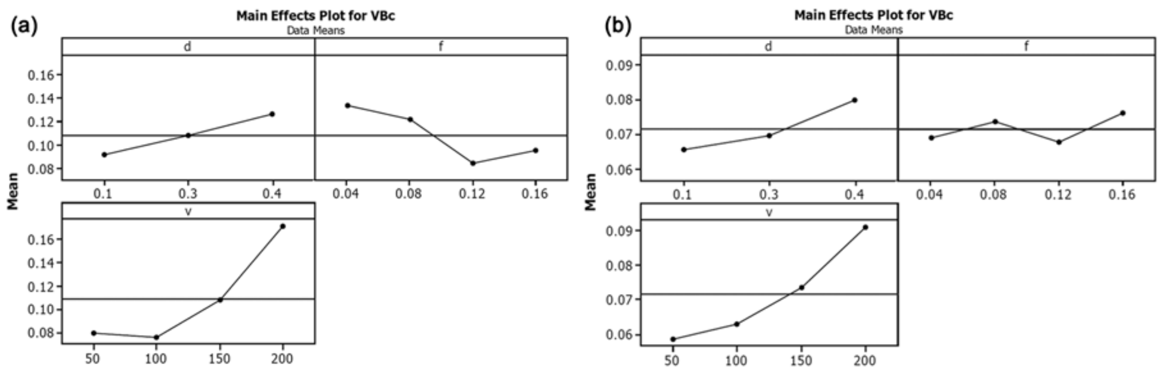

Fig. 11— Main effects plot for Flank wear (a) dry (b) MQL.

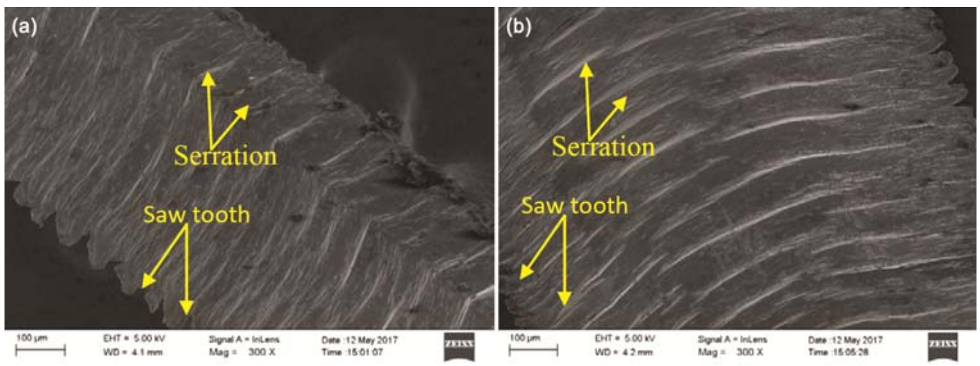

Fig. 12 — SEM micrograph of chip under**(a)** Dry and (b**)** MQL condition of run 4 (*v* = 200 m/min; *f* = 0.16 mm/rev; *d* = 0.1 mm).

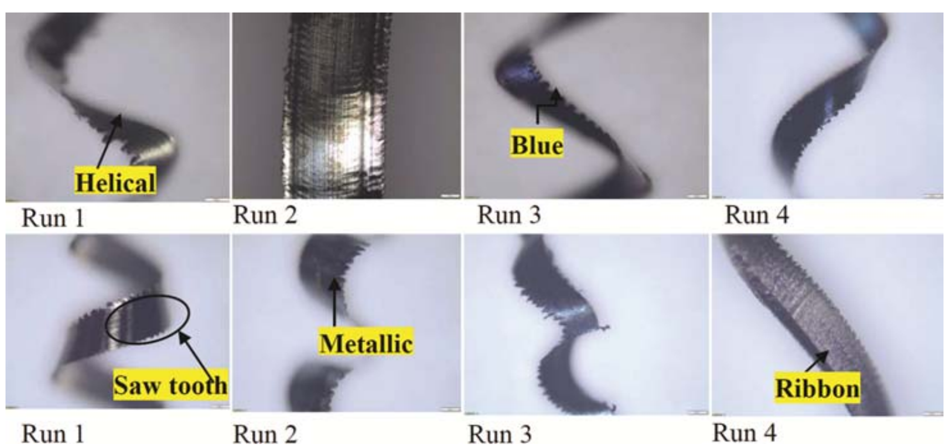

Fig. 13 — Optical image of chip (a-d**)** Dry and (e-h) MQL.

Table 5 — ANOVA for VBc (MQL).

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Contribution %	Remarks
d	2	0.00043	0.00043	0.00021	7.03	0.074	16.47	Insignificant
f	3	0.00013	0.00022	0.00007	2.46	0.24	4.98	Insignificant
v	3	0.00195	0.00195	0.00065	21.19	0.016	74.71	Significant
Error	3	0.00009	0.00009	0.00003			3.84	
Total	11	0.00261						

S = 0.00554 R^2 = 96.47% R^2(adj) = 87.07%

Table 6 — Chip morphology under dry and MQL.

Run No.	Dry turning		MQL assisted turning	
	Chip shape	Chip colour	Chip shape	Chip colour
1	Helical (Saw tooth)	Metallic	Helical (Saw tooth)	Metallic
2	Helical (Saw tooth)	Metallic	Helical(Saw tooth)	Metallic
3	Helical (Saw tooth)	Blue	Helical (Saw tooth)	Metallic
4	Helical (Saw tooth)	Blue	Ribbon(Saw tooth)	Metallic
5	Helical (Saw tooth)	Blue	Ribbon(Saw tooth)	Metallic blue
6	Helical (Saw tooth)	Blue	Ribbon (Saw tooth)	Metallic blue
7	Helical (Saw tooth)	Metallic	Helical (Saw tooth)	Metallic
8	Ribbon (Saw tooth)	Metallic	Ribbon (Saw tooth)	Metallic
9	Helical (Saw tooth)	Blue	Ribbon (Saw tooth)	Metallic
10	Ribbon (Saw tooth)	Blue	Helical(Saw tooth)	Metallic
11	Helical (Saw tooth)	Blue	Ribbon (Saw tooth)	Metallic
12	Ribbon (Saw tooth)	Metallic	Helical (Saw tooth)	Metallic

$R^2 = 99.78\%$; R^2 (adj) = 98.77% … (3)

$Ra = 0.166200 + 2.108300\ d + 4.87500\ f - 0.006800\ v - 2.458300\ d^2 - 17.968800\ f^2 + 0.000000\ v^2 - 0.937500df - 0.003700\ dv + 0.006300fv$, $R^2 = 99.93\%$; R^2 (adj) = 99.63% … (4)

Thus, the model established by regression technique can be efficient to anticipate to the point prediction of roughness of machined surface and tool wear during hard turning.

3.6 Tool life, dimension deviation and cost aspects under Dry and MQL

In the present work, tool life, surface roughness, auxiliary flank wear and dimensional deviation are assessed considering parametric combinations such as $d1$-$f1$-$v2$ (d = 0.1 mm, f = 0.04 mm/rev and v = 100 m/min) under dry and MQL surroundings. The development of flank wears for (PVD TiAlN) coated carbide tool is steadily progressing along with the machining time. The flank wear images mentioned in Fig. 14 (dry condition) indicate that flank wear increases rapidly due to rubbing which accelerates abrasion and adhesion phenomena whereas under MQL, it is mainly due to abrasion. The initiation of abrasion phenomena is observed at a time span of 5.19 min under dry and 4.98 min for MQL condition. Whereas chipping of insert starts at 15.62 min under dry but under MQL condition chipping takes place at 55.63 min. The life of the tool has substantially improved under MQL assisted condition. Due to prolonged machining operation under MQL condition, catastrophic failure of cutting insert is observed at 80.84 min. Although, turning under MQL assisted condition reduces the friction between the insert and work-specimen surface and results in lowering the temperature generation due to a compressed mixture of air and oil (lubricant). Machining under dry circumstances experiences tool life of 36.39 min whereas; under MQL assisted machining surrounding encounters tool life of 80.84 min. This outcome signifies that the tool life in machining under MQL is 122.15 % greater than dry condition. Thus increasing in tool life is noticed under MQL, similar findings were reported by Gupta *et al.*[42].

The variation in surface roughness along with the machining time is shown in Fig. 15a under dry and MQL circumstance. The comparison graph reveals that surface roughness enhances with machining time but a higher value of surface roughness can be noticed under dry condition due to excessive temperature and stresses at tool-nose contact. Whereas, surface roughness values are significantly reduced under MQL circumstances in comparison to dry condition (Fig. 15a) which can be contributed to the superior performance of the lubricant. Also, surface roughness at the end of tool life under MQL condition is reduced by 4.714 % compared to dry. The auxiliary flank wear (Vs) was significantly reduced in MQL assisted turning and graphically displayed in Fig. 15b. Under MQL condition, relatively 13.16 % lower auxiliary flank wear is noticed compare to dry. In each case, MQL enhances the quality of turned surface relative to dry cutting by controlling the development of auxiliary flank wear, degradation of the auxiliary cutting edge. With the application of MQL, flank wear width reduces which may lead to better surface finish relative to a surface obtained in dry cutting.

Influence on dimensional accuracy under dry and MQL machining circumstances is shown in Fig. 16. Finish hard turning under MQL condition promotes dimensional accuracy and provide enhanced results. The rise in temperature expedites the rate of growth of auxiliary flank wear and thermal growth of work specimen enhances[43]. As a significant amount of heat is carried away by the MQL fluid, the temperature at the cutting zone and dimensional deviation of the work-specimen is significantly reduced.

Mathematical models for flank wear and surface roughness versus machining time have been presented through quadratic regression approach to assess the tool life of insert under dry and MQL condition utilizing parameters such as *d* = 0.1mm, *f* =0.04 mm/rev, *v* = 100 m/min respectively. Quadratic models are found to be significant because of higher correlation coefficients i.e. R^2 and R^2 (adj), respectively[44].

$$VBc\ (Dry) = 0.037589 + 0.006965\ Tc - 0.000067\ Tc^2 \quad \ldots (5)$$

R-Sq = 99.43% R-Sq (adj) = 99.15%

$$VBc\ (MQL) = 0.023099 + 0.003060\ Tc - 0.000011\ Tc^2 \quad \ldots (6)$$

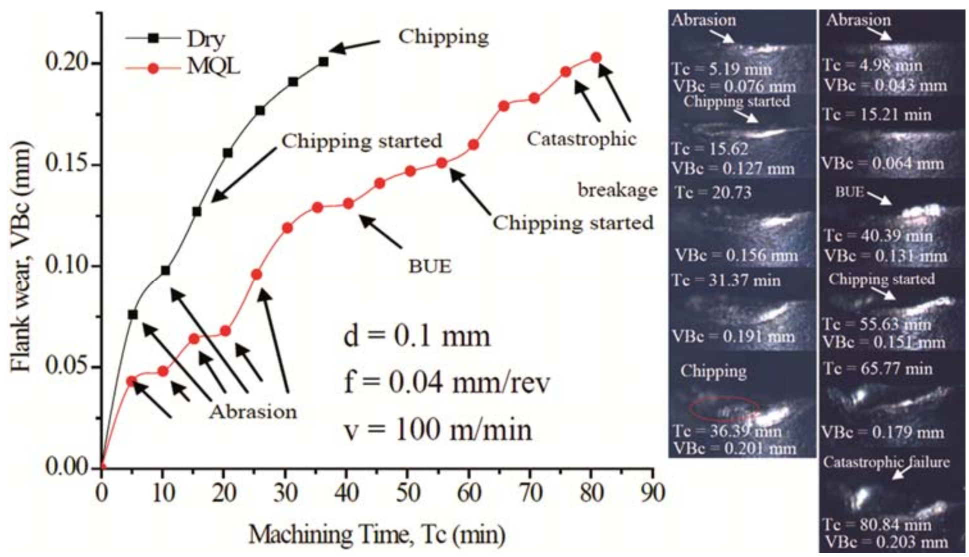

Fig. 14 — Flank wear vs. machining time at v = 100 m/min, f = 0.04 mm/rev and d = 0.1 setting under dry and MQL surrounding.

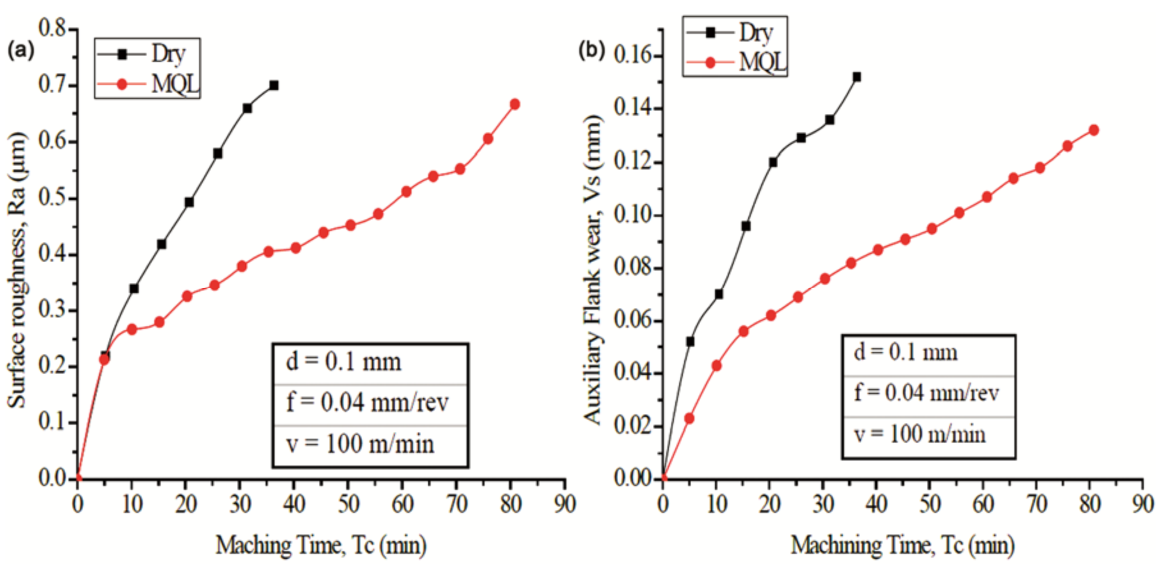

Fig. 15 — (a) Graphical representation of a surface roughness and (b) auxiliary wear along with machining time at *v* = 100 m/min, *f* = 0.04 mm/rev, *d* = 0.1 condition under dry and MQL environment.

Table 7— Comparative economic assessment of PVD TiAlN insert under dry and MQL.

Cutting factors and conditions: TiAlN coated carbide L = 100 mm, D = 50 mm, VBc = 0.2 mm, T_i = 5 min, Test piece = AISI 4340 (50±1 HRC)

Sl. No	Type of costs	v = 100 m/min, f = 0.04 mm/rev, d = 0.1 mm	
		Dry	MQL
1	m = 500 INR (dry) and 525 INR (MQL)	INR 8.33 /min	INR 8.75 /min
2	T_c	3.927 min	3.927 min
3	$m.T_c$	INR 32.712	INR 34.361
4	T_l	36.39 min	80.84 min
5	$m.\ T_i\ (T_c/\ T_l)$	INR 4.494	INR 2.125
6	n	INR 127	INR 127
7	$n(T_c\ /\ T_l)$	INR 13.705	INR 6.169
8	C	INR 50.911	INR 42.655

m = Cost of CNC lathe and operator, T_c= Machining time, [$m.T_c$]= Machining cost per turn, T_l = tool life for cutting tool, [$m\ T_i\ (T_c\ /\ T_l)$] = Tool replacing cost per turn, (n) = Mean value of single cutting edge, [$n\ (T_c\ /\ T_l)$] = Cutting tool cost per turn, (C) = Total machining cost per turn = (3 + 5 + 7).

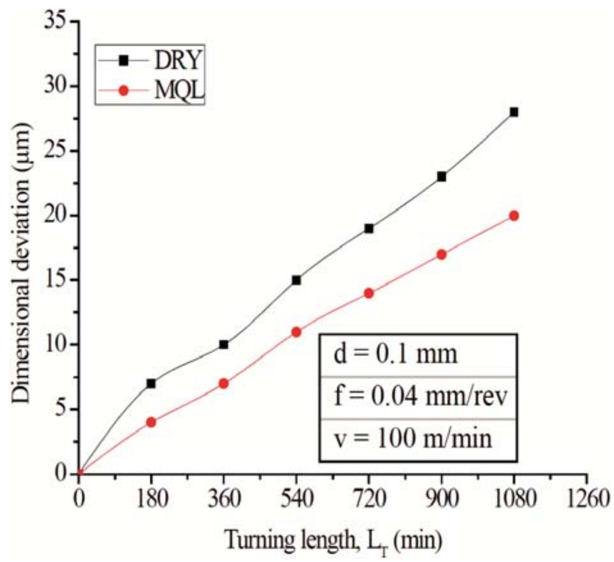

Fig. 16 — Graphical illustration of dimensional deviation versus turning length.

R-Sq = 98.21% R-Sq (adj) = 97.94%

$$Ra\ (Dry) = 0.113113 + 0.022334\ Tc - 0.000167\ Tc^2 \quad \ldots (7)$$

R-Sq = 99.79% R-Sq (adj) = 99.69%

$$Ra\ (MQL) = 0.214294 + 0.004627\ Tc + 0.000007\ Tc^2 \quad \ldots (8)$$

R-Sq = 98.31% R-Sq (adj) = 98.05%

Considering high speed machining which favours high production rates, an economic assessment has been carried out for both environments (More *et al.*[45]). Overall machining cost per turn has been computed on basis of Gilbert's approach and results obtained from tool life under dry and MQL assisted hard turning are displayed in Table 7. Results obtained from cost analysis reveals that the utilization of (PVD TiAlN) coated carbide insert is more economically feasible under MQL environment as the total machining cost per turn is lower (INR 42.655) as compared to dry machining condition(INR 50.911). This leads to 16.21 % cost saving when using PVD TiAlN coated carbide insert under MQL condition.

4 Conclusions

Machining of hardened AISI 4340 steel using PVD TiAlN coated carbide insert under MQL assisted environment has performed well in comparison to dry environment. This experimental investigation shows the improvement in machinability, surface integrity and cost savings aspects of machining under MQL assisted environment. Several other concluding remarks have been drawn from these experimental investigations are as per the following:

(i) Abrasion wear rate and micro-hardness of PVD TiAlN coated carbide insert is found to be 0.00024 gm/min and 1792 HV respectively indicating higher wear resistance of cutting inserts.

(ii) Tensile residual stresses (+71.6 ± 9.8 MPa) under dry condition induced a higher rate of flank wear (0.122 mm) and surface roughness (1.00 µm) compared to MQL condition with a compressive residual stress of -89.3 ± 8.2MPa and flank wear 0.092 mm and surface roughness of 0.88 µm.

(iii) The hard turning of AISI 4340 steel generates a complex structure i.e. tempered martensite which is dispersed evenly under MQL as compared to dry machining. Machining under MQL condition results in finer groove lines and superior surface finish along with the restriction of surface degradation phenomena such as material side flow and ridges as compared with dry machining.

(iv) MQL shows better performance in terms of reduction in the growth of flank wear compared to dry and flank wear value lie well within failure criterion of 0.2 mm. Abrasion was reported to be the key mechanism governing the wear at the flank surface. Cutting speed predominantly influences wear at flank face.

(v) Superior surface quality is observed under MQL assisted hard turning compared to dry condition and surface roughness value remains well within 1.6 µm. Surface roughness tends to increase with the increase of feed rate and cutting speed in both the machining conditions.

(vi) Formation of a white layer on the chip surface was not experienced under both the cutting conditions. Saw-tooth formation and serration on the upper free surface of the chip were observed under both the condition. Metallic colour chips were encountered under MQL assisted machining, while machining under dry condition results in blue colour chips.

(vii) Establish empirical models establishes the dominance of fit and higher statistical significance under both dry and MQL cutting condition.

(viii) At parametric condition i.e. $d1$-$f1$-$v2$ (d = 0.1 mm, f = 0.04 mm/rev and v = 100 m/min), tool life under dry condition is noticed to be 36.39 min while under MQL condition, tool life is 80.84 min. Thus, tool life under MQL is 122.15 % greater than the dry condition.

(ix) MQL reduces the dimensional deviation and acceleration of auxiliary flank wear with machining time as well as the growth of surface roughness in comparison to dry circumstances. Under MQL condition, auxiliary flank wear is reduced 13.16 % and surface roughness at the end of too life condition is reduced by 4.714 % compared to dry condition during hard machining.

(x) MQL Machining with PVD TiAlN coated carbide insert is observed to be cost effective as the total machining cost per part is lower i.e. INR 42.655 compared to dry machining i.e. INR 50.911 which takes into account of 16.21 % cost savings using MQL in hard machining.

From comprehensive experimental investigation in finish hard turning of AISI 4340-grade steel, it is concluded that PVD TiAlN coated carbide insert performs exceedingly well under MQL assisted cutting condition compared to dry in the studied range of input variables for responses. Thus, proposed MQL in hard machining is a novel alternative over dry and conventional cooling methods for cleaner production in machining industries due to ecological, economical and environment friendly[46]. Further work may be investigated to study the impacts of variation in nozzle stand-up distance, different orientation in spraying angle of lubricant towards tool tip, chip-tool contact length, cutting temperature, cutting force etc to examine the machinability distinctiveness. The influence of pulsed MQL along with application of nano-particulate is still to be investigated.

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References

1 Rahman S S, Ashraf Md Z I, Amin A K M N, Bashar M S, Ashik Md F K & Kamruzzaman M, *J Clean Prod,* 206 (2019) 180.
2 Maruda R W, Feldshtein E, Legutko S & Krolczyk G M, *Arab J Sci Eng,* 41 (2016) 661.
3 Gupta M K, Sood P K, Singh G & Sharma, V S, *Int J Mater Prod Technol,* 57 (2018) 299.
4 Wang Y, Li C, Zhang Y, Yang M, Li B, Jia D, Hou Y & Mao C, *J Clean Prod*, 127 (2016) 487.
5 Kumar S, Singh D & Kalsi N S, *Mat Today: Proc,* 4 (2017) 3627.
6 Campatelli G & Scippa A, *Proc CIRP*, 55 (2016) 200.
7 Nune M M R & Chaganti P K, *Mat Today: Proceed,* 4 (2017) 1057.
8 Navs V G, Gonzalo O & Bengoetxea I, *Int J Mach Tools Manuf*, 61 (2012) 48.
9 Leppert T & Peng R L, *Prod Eng Res Develop,* 6 (2012) 367.
10 Outeiro J C, Dias A M, Lebrun J L & Astakhov V P, *Mach Sci Technol,* 6 (2002) 251.

11 Saini S, Ahuja I S & Sharma V S, *Mat Manuf Process,* 27 (2012) 583.
12 Liu M, Takagi J I & Tsukuda A, *J Mat Process Technol,* 150 (2004) 234.
13 Dahlman P, Gunnberg F & Jacobson M, *J Mat Process Technol,* 147 (2004) 181.
14 Jomaa W, Songmene V & Bocher P, *Mat Manuf Process,* 31 (2015) 838.
15 Yang M, Li C, Zhang Y, Wang Y, Li B & Hou Y, *Mat Manuf Process,* 32 (2016) 589.
16 Suresh R, Basavarajappa S & Samuel G L, *Measurement,* 45 (2012)1872.
17 Arfaoui S, Zemzemi F & Tourki Z, *Mater Manuf Process,* 33 (2018) 661.
18 Griffiths B J, *J Tribol,* 109 (1987) 525.
19 Ramesh A & Melkote S N, Int *J Mach Tools Manuf,* 48 (2008) 402.
20 Umbrello D & Rotella G, *Mat Sci Technol,* 28 (2012) 205.
21 Spiech G R & Leslie W C, *Metall Transac,* 3 (1972) 1043.
22 Krauss G, *Mat Sci Eng: A,* 273 (1999) 40.
23 Lee W S & Su T T, *J Mat Process Technol,* 87 (1999) 198.
24 Poulachon G R, Bandyopadhyay B P, Jawahir I S, Pheulpin S & Seguin E, *Int J Mach Tools Manuf,* 43 (2003) 139.
25 Altan E, Uysal A & Caliskan, *Int J Mat Product Technol*, 57 (2018) 54.
26 Dosbaeva G K, Hakim M A, Shalaby M A, Krzanowski J E & Veldhuis S C, *Int J Ref Metals Hard Mat,* 50 (2015) 1.
27 Masoudi S, Vafadar A, Hadad A & Jafarian F, *Mat Manuf Process*, 33 (2017) 1011.
28 Davim J P, *Machining: Fundamentals and Recent Advances*, Springer (2008), ISBN: 978-1-84800-212-8.
29 Zou B, Chen M, Huang C Z & An Q L, *J Mat Process Technol,* 209 (2009) 5802.
30 Das S R, Dhupal D & Kumar A, *J Mech Sci Technol,* 29 (2015) 4329.
31 Mia M, Morshed M S, Kharshiduzzaman M, Razi M H, Mostafa M R, Rahman S M, Ahmad I, Hafiz M T & Kamal A M, *Measurement*, 118 (2018) 43.
32 Mia M, Razi MH, Ahmad I, Mostafa R, Rahman SM, Ahmed DH, Dey PR & Dhar NR, *Int J Adv Manuf Technol,* 91 (2017) 3211.
33 Mia M, Rifat A, Tanvir Md. F, Gupta M K, Hossain Md J & Goswami A, *Measurement,* 129 (2018) 156.
34 Mia M, Al Bashir M, Khan MA & Dhar NR, *Int J Adv Manuf Technol,* 89 (2017) 675.
35 Mia M, Dey P R, Hossain M S, Arafat Md T, Asaduzzaman Md, Ullah Md S & Zobaer S M T, *Measurement,* 122 (2018) 380.
36 Mia M, *Measurement,* 121 (2018) 249.
37 Singh G, Gupta M K, Mia M & Sharma V S, *Int J Adv Manuf Technol,* 97 (2018) 481.
38 Dogra M, Sharma V S, Sachdeva A, Suri N M & Dureja J S, *Int J Prec Eng Manuf,* 11 (2010) 341.
39 Sobiyi K & Sigalas I, *Mach Sci Technol,* 19 (2015) 479.
40 Sharma A K, Tiwari A K & Dixit A R, *J Clean Prod,* 127 (2016) 1.
41 Hosseini S B, Klement U, Yao Y & Ryttberg K, *Acta Materialia,* 89 (2015) 258.
42 Gupta M K, Pruncu C I, Mia M, Singh G, Singh S, Prakash C, Sood P K & Gill H S, *Mater*, 11 (2018) 2088.
43 Dhar N R, Islam S & Kamruzzaman M, *G.U. J Sci,* 20 (2007) 23.
44 Ray S, Rout A K & Sahoo A K, *I J Eng Mat Sci*, 25 (2018) 169.
45 More A S, Jiang W, Brown W D & Malshe A P, *J Mat Process Technol,* 180 (2006) 253.
46 Mia M, Gupta M K, Singh G, Królczyk G & Pimenov D Y, *J Clean Prod,*187 (2018) 1069.