Effect of Cutting Parameters on Power Consumption and Tool Wear during Turning of EN31 Steel under Minimum Quantity Solid Lubrication

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Abstract— This paper reports the comparative investigation of the effect of cutting parameters i.e. cutting speed, feed and depth of cut on power consumption and too wear during turning operation of EN31. Three cooling techniques were employed during the turning operations of which one is Minimum Quantity Solid Lubrication (MQSL). The powder of Calcium Fluoride used as a solid lubricant and mixed with SAE 40 oil, which was used as an MQSL cooling technique. The experimental results highlight the power consumption was less during the MQSL cooling technique. Further, the tool wear was also less in MQSL cooling compared to other cooling technique.

Index Terms— Calcium Fluoride, Minimum Quality Solid Lubrication (MQSL), Turing,

I. Introduction

Machining is classified as one of the manufacturing processes in which the desired shape of components is produced through a removal of unnecessary material in the form of the chip. The cutting action achieved is through relative motion between the cutting tool and the work-piece. The cutting tool material is harder than the work-piece material. The mechanism involved in the machining process is a plastic deformation of work-piece through shear action, where lots of friction occurs in the contact area of the cutting tool and work-piece [1].

Due to friction, lots of heat in the cutting zone. The cutting parameters like cutting speed, feed and depth of cut and work piece are mainly responsible for heat generation. Fig. 1 depicts the generation and distribution of heat during the machining process. Generally, the metalworking fluid also known as coolant is supplied through a system in high volume to reduce the friction. Such techniques also referred to as flood cooling or wet cooling or conventional cooling technique. The purpose of application of metalworking fluid is cooling at relatively high cutting speeds and lubrication at relatively low cutting speeds between the work-piece and cutting tool.

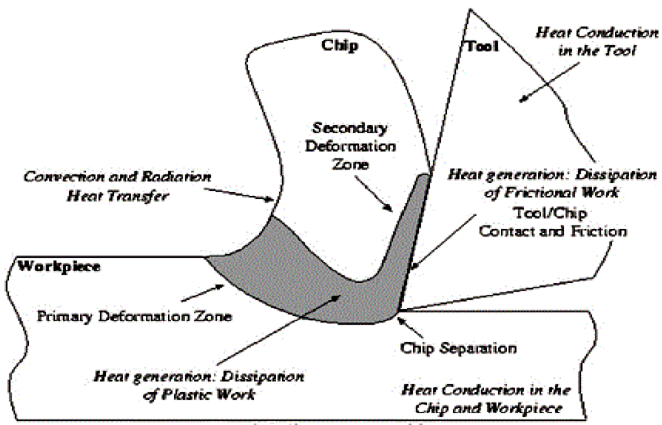

Fig. 1 Generation and distribution of heat during machining process [1]

However, due to disadvantages of conventional cooling technique and innovations in technology, new techniques of cooling like dry cooling, cryogenic cooling; air-cooling, minimum quantity lubrication, and solid lubricants evolved.

Minimum Quantity Lubrication (MQL) is one of the innovative cooling technique. The oil is mixed with high-pressure air and passed through a nozzle to form the aerosol, which is fed to the cutting zone. The function of oil and air in the aerosol provides the lubrication and cooling by droplet evaporation and cooling function respectively. The flow of oil in MQL cooling technique varies from 10 to 500 ml/h and air pressure varies from 2 to 6 bar [2].

Researchers had tried to use solid lubricants, in the powder form during MQL cooling technique, which also shown encouraging results. Some of the solid lubricants used are graphite, molybdenum disulphide, boron nitride, boric acid, silicon dioxide, calcium fluoride etc.

II. Literature Review

Lakic et. Al [3] studied the effectiveness of minimal quantity lubrication (MQL) cooling technique during the turning operation on carbon steel (C45E). The study carried out with a focus on productivity and efficiency of turning operation in comparison of the use of different cooling

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techniques i.e. conventional cooling and minimal quantity lubrication (MQL) technique. Carbide cutting tool was used as a cutting tool and 72 experiments were conducted for each of cooling technique with varying values of cutting speed, feed rate and depth of cut. The results reported with the comparative analysis of output parameters like cutting force, tool life and surface finish which showed that minimal quantity lubrication (MQL) deliver better results than conventional cooling technique.

An investigation was carried out for surface roughness and hardness in the machining of titanium alloy with the polycrystalline diamond cutting tool [4]. The titanium alloy (Ti-6Al-4V) bars of 25 mm diameter used in turning and 27 experiments carried out on CNC lathe machine. The five parameters namely lubricating mode, cutting speed, feed rate, nose radius and depth of cut were identified for study. The lubricating mode was dry, flooded (water-miscible vegetable oil) and minimum quantity lubrication mode (MQL) (palm oil) used during turning tests. The surface roughness improves while the MQL cooling technique employed compare to others and concluded that cutting speed and feed being major affecting factors.

Shashidhara and Jayaram [5] carried out the experimental investigation for cutting power and material removal rate for turning and drilling operation respectively. The study was carried out with non – edible oils namely pongam and jathropha along with mineral oil as cutting fluid being applied through MQL. The cutting power and material removal rate (MRR) was found to be reduced during turning operation and during drilling operation respectively when both vegetable oils used as cutting fluid compared to mineral oil.

Rao and Krishna [6] examined the execution of boric acid as a solid lubricants in turning operation. The trials completed with EN 8 steel (heat treated) and carbide cutting tips utilized as a cutting tool. A experimental set up was produced and solid lubricant provided continuously at the flow rate of 2 – 3 gm/min to the cutting zone. The process parameters like cutting rate, feed rate and depth of cut chose amid turning under dry, flood cooling and solid lubricant cutting condition. The cutting force and tool wear reduced during the use of boric acid powder as coolant compared to other cutting environments. The study also concluded that better surface finish achieved in case of boric acid powder assisted machining. Further concluded that use of solid lubricant through (MQL) technique proved to be an economical option for industry.

Krishna et. al. [7] had researched the execution of nano boric corrosive powder blended with SAE 40 and coconut oil amid turning activity of AISI 1040 steel. The boric corrosive powder, with 50 μm molecule estimate blended in SAE 40 and coconut oil in shifting extent of 0.25%, 0.5% and 1% by weight was utilized as a greasing up oil (cutting liquid) and its impact was explored. The researchers concluded that cutting temperature, tool flank wear and surface roughness decreased significantly with nano lubricants and better performance in terms of output parameters observed at 0.5% nano boric suspensions in coconut oil.

Sayuti et. al [8] studied the effect of the use of silicon dioxide (SiO_2) particles mixed with mineral oil on the surface roughness and tool wear during hard turning of AISI 4140 steel. The mist of silicon dioxide nano-lubrication used in minimum quantity lubrication mode. The cylindrical work piece of AISI 4140 steel of diameter 30 mm, length of 200 mm through hardening with 52 HRC being turned with coated carbide tool at cutting speed 120 m / min, feed rate 0.15 mm / rev and at 0.5 mm depth of cut. Total 16 experiments were conducted as per the Taguchi Optimization method using a standard L16 orthogonal array for different levels of input parameters. The input parameters were nano-lubrication concentration, nozzle angle and air pressure selected for study and their effect on tool wear and surface finish were investigated. The average reading of three experiments for tool wear and surface roughness were taken as a reading of the experiment. It was reported that a better surface finish was obtained with 0.5% nanoparticles concentration, 30° nozzle angle, and less air pressure. The least amount of tool wear was obtained with 0.5 % nanoparticles concentration, 60° nozzle angle, and 2 bar air pressures.

Du et. al. [9] studied the effect of solid lubricants during hard turning. The AISI 52100 steel material, through heat-treated with 58 HRC was selected as work piece material. The diameter of the work piece was 70 mm, turned on a lathe machine. Total 31 experiments were conducted based on the central composite design for different values of parameters like cutting speed, feed rate, effective rake angle, and nose radius. The solid lubricants used for experiments were molybdenum disulfide and graphite of 2 μm average particle size and supplied at the flow rate of 2 gm/min. It was reported that molybdenum disulfide assisted hard turning showed better surface finish in comparison of graphite assisted hard turning.

Abhang and Hameedullah [10] explored the impact of cutting parameters amid turning of alloy steel (EN31 Steel) work piece. The parameters chose for examination were cutting speed, feed rate, depth of cut and tool nose radius. Total 24 tests were led under three cutting condition in particular dry, wet and minimum quantity lubrication (MQL). The cutting oil utilized was of boric acid blended with SAE 40 oil. It was seen that surface finish decreases with an increases in cutting speed and tool nose radius, increases with an increases in feed rate and depth of cut. The examination concluded that turning with boric acid blended with SAE 40 oil through MQL condition is superior to dry and wet turning.

Alberts et. al. [11] investigated the effect of graphite nanoplates in solid lubrication grinding on forces, specific energy and surface finish during surface grinding of hardened D - 2 tool steel. The experimental study was conducted with graphite type, concentration, and size as input parameters. The graphite was mixed in isopropyl alcohol (solvent) and in semi-synthetic, water-based emulsion and being applied through spraying and coating method. It was observed that both the application method of solid lubrication was simple to implement and significantly reduces the grinding forces and specific energy during surface grinding with improvement in surface finish.

III. Experimental Details and Methodology

The focal point of the present examination is to evaluate the execution of solid lubrication blended in oil during turning operation. The solid lubricant blended in oil required to be provided to the cutting zone utilizing Minimum Quantity Solid Lubrication technique. Hence, a minimum quantity solid lubrication (MQSL) setup was developed for injecting solid lubricant mixed in oil at the required pressure. The MQSL setup with different elements is shown in Fig. 2.

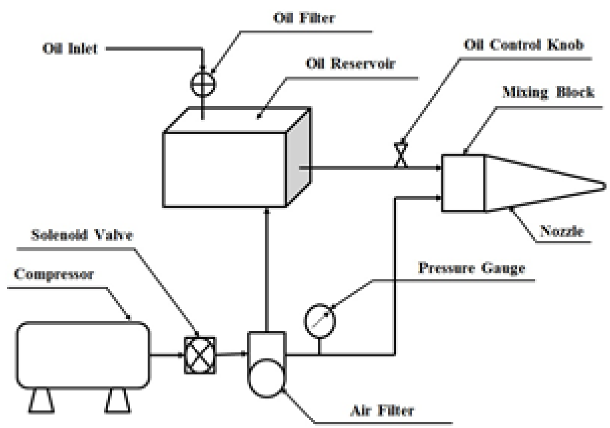

Fig. 2 MQSL set up with different elements

EN31 popularly known as alloy / bearing Steel is selected for the present investigation as it is widely used to manufacture ball screws, forming tools, bearings, cams, and pawls, gauges, punches, etc. Many researchers had used the graphite, molybdenum disulphide, boric acid and calcium fluoride powder however very little work has been reported with the use of calcium fluoride. Hence, the calcium fluoride was chosen for preparing powder mixed cutting fluid to be applied to the machining zone. Calcium fluoride mixed in monograde (SAE 40 oil) engine oil and mist was used as coolant along with conventional cooling technique.

The experiments were performed on a lathe machine. The photograph of the experimental set up along with the stirrer is shown in Fig. 3. The cutting speed, feed, and depth of cut are selected as input process parameters and remaining parameters are kept constant during the all three cutting conditions. The range of all three input parameter selected for study is based on the recommendation of a combination of work piece material and cutting tool material which is shown in Table 1. Total 15 experiments each were performed for three cooling technique as per Box – Behnken Design. All the work pieces were pre-turned depending upon the cutting speed and available spindle speed. The turning length for each work piece was 80 mm.

Table 1 Input Process Parameter with their range

Sr. No.	Process Parameter	Range
1	Cutting Speed	70, 110, 150 m/min
2	Feed	0.1, 0.25, 0.4 mm/rev.
3	Depth of Cut	0.5, 1, 1.5 mm

The turning operation as a part of examinations was done by utilizing coated carbide tips of TN4000 review of Widia make. The tips with a four-layer covering of CVD-TiN-TiCN-Al_2O_3-TiN and with higher cobalt content has great durability, which allows heavy depths of cut and interrupted cuts. The embed assignment according to ISO code is CNMG1204085 TN4000 appeared in Table 2 with its significance.

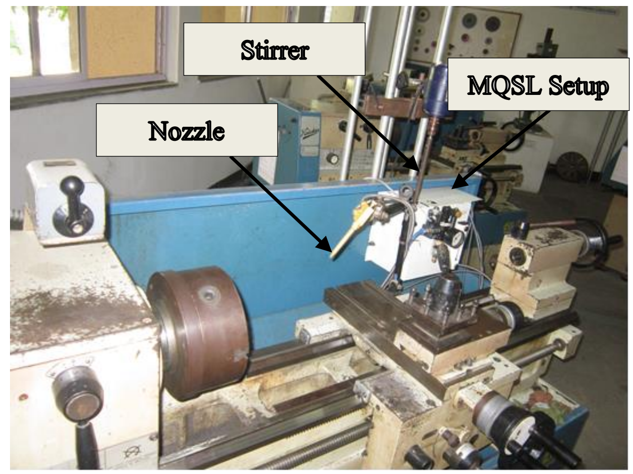

Fig. 3 Experimental Set up on lathe machine

Table 2 Insert Designation with its meaning

Code Letter / Number	Meaning	Code Letter / Number	Meaning
C	Rhomboid - 80°	12	Size of inset – 12 mm
N	Clearance Angle - 0°	04	Insert Thickness – 4 mm
M	Tolerance Class - ± 0.013 mm	08	Corner Radius – 0.8 mm
G	Insert Feature –	5	Medium Roughing

IV. Result and Discussion

The power consumption for a different cutting condition for each cutting environment i.e. dry, wet and MQSL cutting environment was measured and as summarized in Table 3. The Design-Expert software (Version – 8.0.6 for Windows, Educational Version) was used for the analysis and computational work.

Table 3 Measured power consumption during dry cutting environment

Cutting Speed (m/min)	Feed (mm/rev)	Depth of Cut (mm)	Dry Environment Measured Power (Watt)	Wet Environment Measured Power (Watt)	MQSL Environment Measured Power (Watt)
70	0.1	1	320	296	280
150	0.1	1	640	600	560
70	0.4	1	600	520	496
150	0.4	1	1280	1240	1200
70	0.25	0.5	320	240	256
150	0.25	0.5	600	600	560
70	0.25	1.5	640	560	600
150	0.25	1.5	1380	1320	1280
110	0.1	0.5	280	280	280
110	0.4	0.5	560	560	520
110	0.1	1.5	600	560	560

110	0.4	1.5	1336	1320	1160
110	0.25	1	696	680	640
110	0.25	1	720	696	680
110	0.25	1	640	640	640

Based on the analysis, it was found that the 2 Factor Interaction model is the best appropriate model for power consumption for all the three cutting environments. ANOVA is used to check the adequacy of the developed model. Table 4, Table 5 and Table 6 shows the ANOVA for power consumption for dry, wet and MQSL cutting environments and quadratic model as (1), (2) and (3) respectively.

Table 4 ANOVA FOR Power consumption (Dry)

Source	SS	DF	MS	F value	p-value
Model	1718648	6	286441	233.17	< 0.0001
A-Cutting Speed	510050	1	510050	415.19	< 0.0001
B – Feed	468512	1	468512	381.38	< 0.0001
C – Depth of Cut	602802	1	602802	490.69	< 0.0001
A x B	32400	1	32400	26.37	0.0009
A x C	52900	1	52900	43.06	0.0002
B x C	51984	1	51984	42.32	0.0002
Residual	9828	8	1228		
Lack of Fit	6457	6	1076	0.64	0.7164
Pure Error	3371	2	1685		
Cor. Total	1728476	14			
Std. Deviation	35.0495		R^2	0.9943	
Mean	707.4667		Adj. R^2	0.9900	
C V %	4.9542		Pred. R^2	0.9814	

The model's F value (calculated F value) is 233.17 implies that the model is significant. If the model has a very high degree of adequacy for predicting the experimental results, the model's F value should be greater than the tabulated F value at a level of significance α. Thus, the model's F value (F_{-model} = 233.17) was compared with the tabulated F value at a significance level of 0.01 (F0.01, 6, 8 = 6.37) and found greater. The p values less than 0.05 indicate model terms are significant. The R^2 statistics is 99.43 %, which shows that the model provides a strong correlation between independent variables and response (power consumption). The predicated R^2 of 0.9814 is in reasonable agreement with the adjusted R^2 of 0.9900. The lower value of CV% (coefficient of variation) i.e. 4.95 indicates improved precision and reliability of the performed experiments.

$$\text{Power (P)} = 485.7583 - 3.1875A - 1556.67B - 463.5C + 15AB + 5.75AC + 1520BC \quad (1)$$

Where P = Power consumption, A = Cutting Speed, B = Feed, C = Depth of Cut

Table 5 ANOVA FOR Power consumption (Wet)

Source	SS	DF	MS	F value	p-value
Model	1709408	6	284901	308.513	< 0.0001
A-Cutting Speed	574592	1	574592	622.212	< 0.0001
B – Feed	453152	1	453152	490.707	< 0.0001
C – Depth of Cut	540800	1	540800	585.619	< 0.0001
A x B	43264	1	43264	46.850	0.0001
A x C	40000	1	40000	43.315	0.0002
B x C	57600	1	57600	62.374	< 0.0001
Residual	7388	8	923		
Lack of Fit	5724	6	954	1.147	0.5349
Pure Error	1664	2	832		
Cor Total	1716796	14			
Std. Deviation	30.3886		R^2	0.9957	
Mean	674.1333		Adj. R^2	0.9925	
Model	1709408	6	284901	308.513	< 0.0001

The model's F value (calculated F value) is 308.51 implies that the model is significant. If the model has a very high degree of adequacy for predicting the experimental results, the model's F value should be greater than the tabulated F value at a level of significance α. Thus, the model's F value (F_{-model} = 308.51) was compared with the tabulated F value at a significance level of 0.01 (F0.01, 6, 8 = 6.37) and found greater. The p values less than 0.0500 indicate model terms are significant. The "Lack of Fit F-value" of 1.15 implies it is not significant which is good. The R^2 statistics is 99.57 %, which shows that the model provides a strong correlation between independent variables and response (power consumption). The predicated R^2 of 0.9812 is in reasonable agreement with the adjusted R^2 of 0.9925. The lower value of CV% (coefficient of variation) i.e. 4.51 indicates improved precision and reliability of the performed experiments.

$$\text{Power (P)} = 447.133333 - 2.633333A - 1992B - 430C + 17.333333AB + 5AC + 1600 \quad (2)$$

Where P = Power consumption, A = Cutting Speed, B = Feed, C = Depth of Cut

Table 6 ANOVA FOR Power consumption (MQSL)

Source	SS	DF	MS	F value	p-value
Model	1448400	6	241400	225.7200	< 0.0001
A-Cutting Speed	484128	1	484128	452.6817	< 0.0001
B – Feed	359552	1	359552	336.1975	< 0.0001
C – Depth of Cut	492032	1	492032	460.0723	< 0.0001
A x B	44944	1	44944	42.0247	0.0002
A x C	35344	1	35344	33.0482	0.0004
B x C	32400	1	32400	30.2955	0.0006

Residual	8556	8	1069		
Lack of Fit	7489	6	1248	2.3403	0.3293
Pure Error	1067	2	533		
Cor Total	1456956	14			
Std. Deviation	32.7027		R^2	0.9941	
Mean	647.4667		Adj. R^2	0.9897	
Model	1448400	6	241400	225.7200	< 0.0001

The model's F value (calculated F value) is 225.72 implies that the model is significant. If the model has a very high degree of adequacy for predicting the experimental results, the model's F value should be greater than the tabulated F value at a level of significance α. Thus, the model's F value (F_{-model} = 225.72) was compared with the tabulated F value at a significance level of 0.01 (F0.01, 6, 8 = 6.37) and found greater. The p values less than 0.05 indicate model terms are significant. The "Lack of Fit F-value" of 2.43 implies it is not significant which is good. The R^2 statistics is 99.41 %, which shows that the model provides a strong correlation between independent variables and response (power consumption). The predicated R^2 of 0.9721 is in reasonable agreement with the adjusted R2 of 0.9897. The lower value of CV% (coefficient of variation) i.e. 5.05 indicates improved precision and reliability of the performed experiments.

$$\text{Power (P)} = 424.466667 - 2.966667A - 1730B - 321C + 17.666667AB + 4.7AC + 1200BC \quad (3)$$

Where P = Power consumption, A = Cutting Speed, B = Feed, C = Depth of Cut

The quadratic models for power consumption as created through the ANOVA system should be approved through affirmation tests. Keeping in mind the end goal to check the adequacy of the model created, four affirmation tests for each cutting conditions i.e. dry, wet, MQSL were conducted, and the responses were measured as appeared in Table 7, Table 8 and Table 9 for dry, wet and MQSL cutting condition separately.

The percentage of error power consumption is within the permissible limits. So, the response model for power consumption for each cutting environment can be used to predict the power consumption values for any combination of cutting speed, feed and depth of cut within the range of experiment performed.

The surface roughness was also measured for the different cutting environment along with the power consumption. It was observed that the power consumption and surface roughness was marginally better in case of MQSL cutting environment compare to the dry and wet cutting environment. This is attributed to lubrication effect used during Minimum Quantity Solid Lubrication. In addition to this, solid lubricant has provided a thin film of lubrication between tool and work piece interface resulting lower tool wear leading to improvement in surface finish.

Table 7 Validation Experiments (Dry)

Sr. No.	Cutting Speed (m/min.)	Feed (mm/rev.)	Depth of Cut (mm)	Power (W)	
				Experimental	Predicated
1	70	0.25	1.5	640	615
2	150	0.4	1.0	1296	1292
3	130	0.4	0.52	696	693
4	85	0.18	1.16	496	507

Table 8 Validation Experiments (Wet)

Sr. No.	Cutting Speed (m/min.)	Feed (mm/rev.)	Depth of Cut (mm)	Power (W)	
				Experimental	Predicated
1	70	0.25	1.5	600	567
2	150	0.4	1.0	1256	1285
3	121	0.2	1.4	896	879
4	104	0.18	0.8	440	446

Table 9 Validation Experiments (MQSL)

Sr. No.	Cutting Speed (m/min.)	Feed (mm/rev.)	Depth of Cut (mm)	Power (W)	
				Experimental	Predicated
1	70	0.25	1.5	576	556
2	150	0.4	1.0	1200	1212
3	85	0.18	0.7	360	348
4	121	0.2	1.5	880	875

The different coated carbide inserts were used to perform experiments for each cutting environments i.e. dry, wet and MQSL. A single insert was used to perform all the experiment of the same cutting environment. Tool life is one of the critical aspects in any machining process. Fig. 4 shows the comparison of flank wear after each machining condition experiments. It is evident from the comparison that, as expected highest value of flank wear is observed in dry machining due to the absence of lubricating action. MQSL has performed better by increasing tool life as the coefficient of friction is reduced in presence of solid lubricant particles between tool-work interface.

It is also evidence of the superior lubricating quality of solid lubricant. However, flank wear observed in wet machining is slightly higher than that of MQSL may be because the lubricant failed to penetrate and retain in the machining area. The results show a trend that is similar to the experiments performed by Kamata and Obikawa [12] performed turning operation on Inconel 718 considering various coating tools and achieved good surface finish and improved tool life than that in the wet and dry machining. Another work reported by Deiab et. al. [13] using vegetable oils in MQL and compared the tool wear, surface roughness and energy consumption of different cooling strategies during the turning of Ti6Al4V and proved MQL to be an overall sustainable alternative. Scanning Electron Microscopy (SEM) images of three-coated carbide inserts were taken after all experiments and shown in the Fig. 5, Fig. 6 and Fig. 7 for dry, wet and MQSL cutting environments respectively

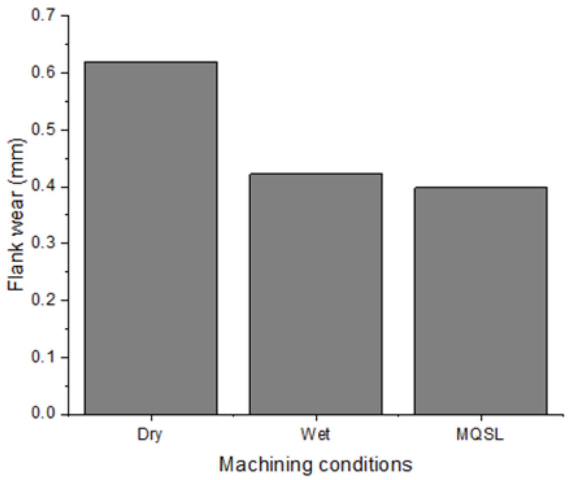

Fig. 4 Comparison of flank wear after each machining conditions

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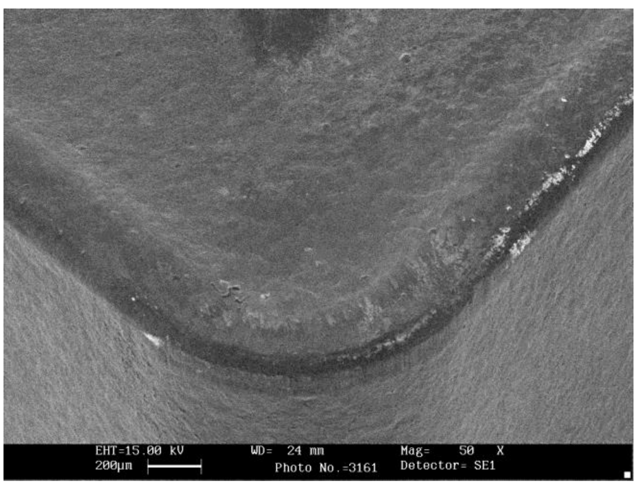

Fig. 5 SEM image of Coated Carbide Tip (Dry)

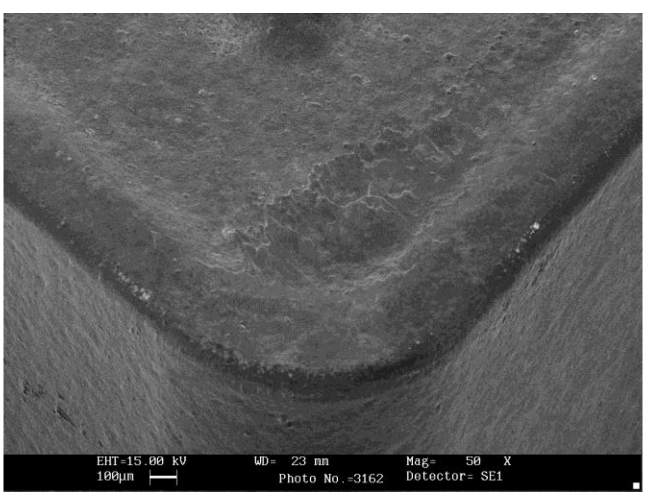

Fig. 6 SEM image of Coated Carbide Tip (Wet)

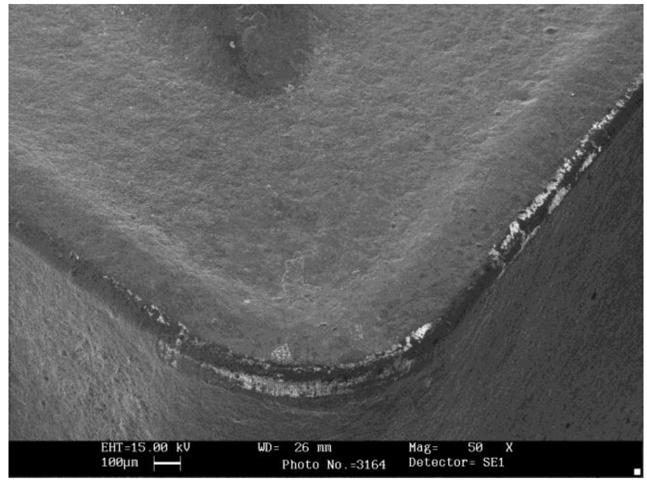

Fig. 7 SEM image of Coated Carbide Tip (MQSL)

Looking from the comparison of SEM images, the abrasive scratch marks appeared in the flanks. It is evident that the insert used for the dry cutting environment had maximum scratch marks compare to wet and MQSL cutting environment. This confirms the strong impact of cutting fluid during turning. It is seen that the crater wear is more in the insert used for the wet cutting environment than of MQSL cutting environment. This is due to the solid lubricant particle mixed cutting oil, which provides better lubrication and absorbs more heat produced during turning. Vagnorius and Sorby [14] used the ceramic inserts along-with pressurized cooling during the machining of Inconel 718. The tool life was slightly poorer and chip breaking was improved compared to conventional cooling. From the SEM analysis, it is observed that the mechanism of flank wear is adhesion or abrasion. There is no any evidence of formation of the built-up edge due to better lubrication efficiency in case of wet and MQSL machining.

V. Conclusion

In this investigation, the experiments were conducted for three cutting environments during turning of EN31 alloy steel including MQSL technique as one of them. Two response parameters namely power consumption and tool wear were studied. Data collected for power consumption during turning operation are used to develop the model for each cutting environments. The predicted values of models are compared with the experimental results, which were found very close with 5% error amongst the values. Further, less tool wear observed on the carbide tip used during the MQSL cutting environments compare to the other two. It is evident that use of solid lubricant along with minimum quantity lubrication is one of the better methods of cooling compared to dry and wet cooling.

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