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Experimental investigation of machining parameter under MQL milling of SS304

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Abstract. Minimum quantity lubrication (MQL) or near dry machining has been recognized by many researchers and industrialist in order to move one step ahead towards the green manufacturing. MQL assisted machining reduces the harmful environmental impact caused by flood coolant and machining cost. In this paper an attempt has been made to study the impact of oxygen as a carrier gas in MQL during end milling of austenitic stainless steel grade SS304. Also, the machining performance under conventional MQL with air and dry machining have been studied. The evaluation was done on tool wear, surface roughness and cutting forces under two distinct cutting speeds i.e. 75 m/min and 100 m/min. Investigation brings to light that presence of oxygen is susceptible in the case of machining of SS304, it provides extra protective oxide layer near the tool chip interface. Consequently, increased tool life, reduced surface roughness and cutting forces when compared to conventional MQL assisted milling.

Keywords: Minimum quantity lubrication, SS304, tool wear, surface finish, cutting forces

1. Introduction

Austenitic stainless steel grade SS304 has wide ranging applications in aerospace industries, chemical industries, cryogenic vessels etc. Due to its properties such as low heat conductivity, high tensile strength and high ductility these steels are considered as difficult to machining. Machining of austenitic stainless steel are usually convoyed by a number of hitches such as irregular wear and built up edge (BUE) on the tool flank face and rake face, respectively [1]. High production machining of steel inherently generates high cutting zone temperature. Such high temperature causes dimension deviation and premature failure of cutting tools. At high speed machining flood coolant are not effective at the chip tool interface. Thus the machining to be effective Minimum Quantity Lubrication (MQL) came into existence. MQL can be briefed as very small quantity of biodegradable lubricants are sprayed at the tool chip interface at certain angle and distance through nozzle with the assistance of compressed air or gases. The quantity of MQL ranges typically in order of 100 ml/hr which is three to four times lower in magnitude of that of flood coolant. The cutting performance of MQL machining is superior than dry cut and conventional machining with good cutting fluid supply because MQL provides the assistance mainly by lowering the cutting temperature which improves the chip tool interaction and maintains sharpness of the cutting edges [2]. MQL is a good replacement for flood coolant which reduces the environmental impact and, manufacturing cost in the form of improved tool life. Khan et al.[3] have studied the effect of MQL on turning of AISI9310 alloy steel using vegetable oil based cutting fluids. They measured the tool chip interface temperature and surface roughness and found that MQL produced lowest temperature and surface roughness compared to dry and flooded condition .They concluded that vegetables oil was very effective to reduce cutting temperature compared to flood coolants. Rehman et al. [4] have studied the effect of MQL (8.5ml/hr.) in end milling of 718HH steel. They noticed that the cutting forces generated during flooded condition and MQL are almost equal. Liao and Lin [5] noticed that MQL can provide extra oxygen to promote the formation of protective oxide layer in between the chip tool interface. In MQL, flow rate, mist droplets, angle of nozzle, nozzle discharge pressure at the cutting tool, plays a vital role in MQL optimization [6]. Dhar et al. [7] found that that drilling of alloys which has high ductility is difficult under dry machining. Inasaki et al. [8] carried out the tribological action of MQL media and atmospheric carrier gases in machining of aluminum. They studied the adsorption behavior onto the metal surfaces in close connection with the cutting performance of a lubricant, synthetic ester and carrier gases in the practical machining. In particular, Oxygen resulted in detrimental cutting phenomena in MQL machining of aluminum. Cakir et al. [9] applied MQL technique in the turning of AA7075 and AA2024 aluminum alloy. It was observed that increased feed rate and cutting speed had a negative effect on the surface quality. Hadad et al. [10] have experimented MQL with turning of AISI 4140 steel alloy and found out the effect on machining forces, surface roughness and temperature. The tool chip interface temperature was approximately 350°C lower than that in dry turning when oil mist was supplied from both the nozzles to the rake and flank faces. Similarly, the tool temperature was about 200 °C lower when only single nozzle with oil mist was supplied to the rake face alone. High speed machining of titanium alloys under dry and MQL machining with (nc-AlTiN)/(a-Si_3N_4) coating and (nc-AlCrN)/(a- Si_3N_4) coating tool were used for comparative study of wear performance. MQL condition showed lubricating and cooling effect as well as wear rate for (nc-AlTiN)/(a- Si_3N_4) coated tool were less compared to the (nc-AlCrN)/(a- Si_3N_4) coated tool. MQL works as protective layer for nano coated tools and at the same time cooling and lubricating effect is depicted [11]. Kamata et al. [12] conducted experiment on high speed MQL finish-turning of Inconel 718 with three coated tool such as TiCN/Al_2O_3/TiN (CVD), TiN/AlN superlattice (PVD) and TiAlN (PVD). There results depicted that TiCN/ Al_2O_3/TiN (CVD) coated with MQL conditions showed the best performance while TiN/AlN superlattice (PVD) exhibited second best performance with MQL condition. It was found that argon as carrier gas in oil mist instead of the air plays a vital role in cooling of cutting point during machining of Inconel 718. Micro-liter Lubrication machining of Inconel 718 experimented by Obikawa et al. [13]. If Lubrication quantity was less than 1.0 ml/hr which is 10 to 100 times smaller than the usually consumed is stated as micro-liter lubrication. Concentrated spraying of oil mist with shortening of the distance between the specially designed nozzle and the cutting interface has quite effective influence on cutting performance with MQL condition. The main objective of present work was to experimentally investigate the performance of oxygen as a carrier gas on tool flank wear, surface roughness and chip morphology in MQL assisted milling of SS304 work material in comparison with conventional MQL with compressed air and dry conditions at different cutting speeds.

2. Experimentation

The milling operations were carried out in three axes CNC milling machine manufactured by BFW, India. The workpiece material selected was austenitic stainless steel grade SS304 with dimension of 184×75×11 mm. The hardness value of the workpiece was found to be 30 HRc. The chemical composition of the workpiece is tabulated in table 1. Before experimentation, surface of the workpiece was face milled to get rid of the hard particles such as oxides and carbides. The minimum quantity lubrication system used was Dropsa VIP5. The flow rate of lubricating oil in MQL assisted machining was maintained at 80 ml/hr and the pressure of carrier gas/air was set at 0.5 MPa for all the experiments. The lubricant used was LRT-30 (Viscosity 24 cSt at 40^0C, Flammability point ^{0}C: >220; Specific weight kg/liter at 15^0C:0.9). The tool insert used was single layer TiAlN PVD coated carbide inserts with ISO designation of APMT 1135 PDER M2 VP15TF manufactured by Mitsubishi. The end mill cutter of diameter 10 mm with single insert was used. The machining process parameters for the experimentation were selected from various literature reviews and tabulated in table 2. Cutting forces during milling was measured using Kistler 9257B dynamometer. For every experiment, a new insert was used and respective analysis was done for tool flank wear. After every experiment, the surface roughness was measured using Mahr's talysurf profilometer. The chips were collected at the end of each trail for chip morphology analysis. Figure 1 depicts the photograph experimental setup.

Table 1. Chemical composition of work piece material.

Element	Ni	Cr	C	P	S	Si	Fe
Composition wt%	8.5%	19%	0.08%	0.04%	0.03%	1%	Balance

Table 2. Machining process parameters

Cutting speed (m/min)	75	100
Feed (mm/rev)	0.05	
Depth of cut (mm)	0.5	
MQL (ml/hr)	80	
Carrier gas/air pressure (MPa)	0.5	

Figure 1. Photograph of experimental setup (a)MQL suppy system and CNC milling (b) Close up view of tool, workpiece and MQL nozzle set up

3. Results and discussion

3.1. Tool wear analysis

Milling is a discontinous machining process where the tool cutting egde enters and exits the workpeice numerous times per second. The tool wear is sensitive to the speed and feed rate in milling [13]. Figure 2 shows the flank wear results for the three different cutting environments at 75 and 100 m/min cutting speeds. It is observed from the results that there is no significant variation on flank wear at low cutting speed (75 m/min). Whereas, at cutting speed of 100 m/min there is a steep reduction of frank wear between dry machining (68.05 µm) and MQL assisted machining conditions (54.34 µm and 47.61 µm respectively for air and oxygen). This could be due to MQL environment resulted in formation of thin film over the cutting edge resulted in lower order flank wear. Further, increase in cutting speed attributes to higher order flank wear. Under dry cut condition there is a 32% increase in flank wear as the cutting speed increased from 75 to 100 m/min. Whereas, under MQL with air and

MQL with oxygen environments the percentage increase in flank wear is 14% and 9% respectively. Figure 3 shows the scanning electron micrographs of tool wear pattern observed for the three cutting environments. During dry cutting (Figure 3 a-b) rapid tool wear occurs in the form of crater, chipping and thermal cracks. Under MQL with air environment (Figure 3 c-d) and MQL with oxygen environment (Figure 3 e-f) micro chipping of cutting edges and flaking of coating have been observed. Further, it is also observed that under MQL with oxygen environment the sharp cutting edge is maintained which results in reduced cutting forces and surface roughness. This phenomenon is mainly due to the formation of compound oxides (Fe,Mn,Si, and Al), which act as a strong barrier for mutual diffusion between carbide tool and steel as observed [5].

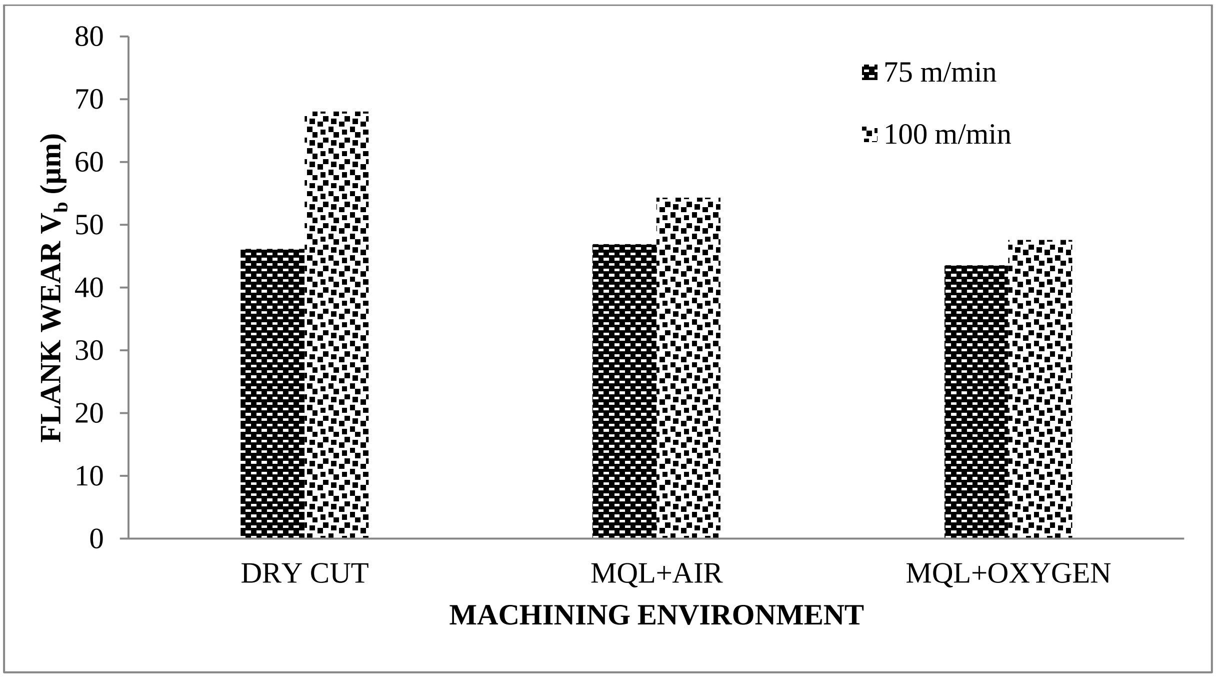
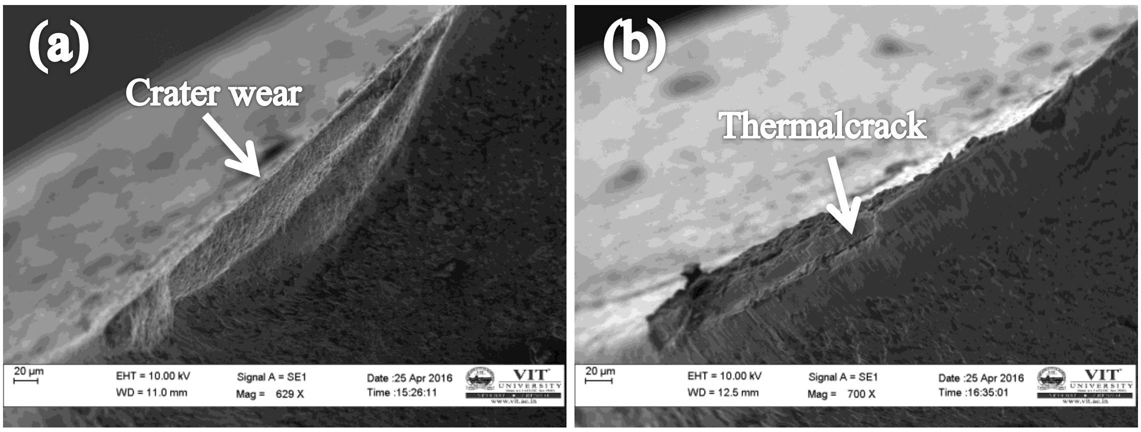


Figure 2. Flank wear V_b (µm) with machining environment



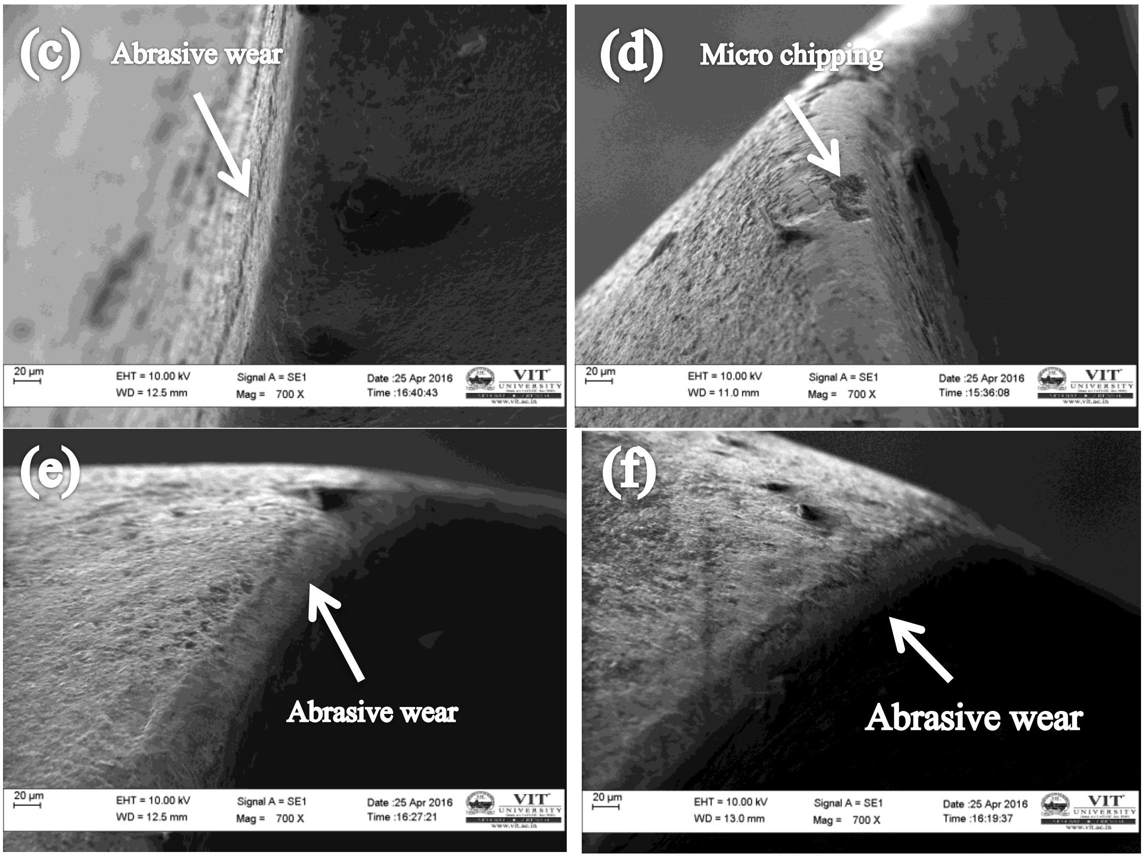


Figure 3. SEM images of flank wear (a) Dry cut 75m/min (b) Dry cut 100m/min (c) MQL with air 75m/min (d) MQL with air 100 m/min (e) MQL with oxygen 75m/min (f) MQL with oxygen 100m/min.

3.2. Analysis of Surface roughness

Figure 4 shows the variation of surface roughness under different machining environments. It is observed that the surface roughness for MQL with oxygen is low comparing to the MQL with air and dry cut. At 75 m/min cutting speed, the surface roughness decreases by 16% and 40% as the machining environment changed from dry to MQL with air and MQL with oxygen respectively. It was also observed that MQL with oxygen is very effective at cutting speed of 75 m/min. A reduction of surface roughness value of 28% and 3.4% compared between MQL with air and MQL with oxygen at 75 m/min and 100 m/min cutting speeds respectively. It shows that MQL with oxygen is effective up to a certain cutting speed and beyond which the reduction of surface roughness is less. The surface roughness value for dry cut increases drastically due to the rise in temperature, which is more intensive at tool-tip. Tool wear is directly related to the surface roughness. i.e more the tool wear more is the surface roughness. MQL with oxygen gives less tool wear thus better surface finish is obtained.

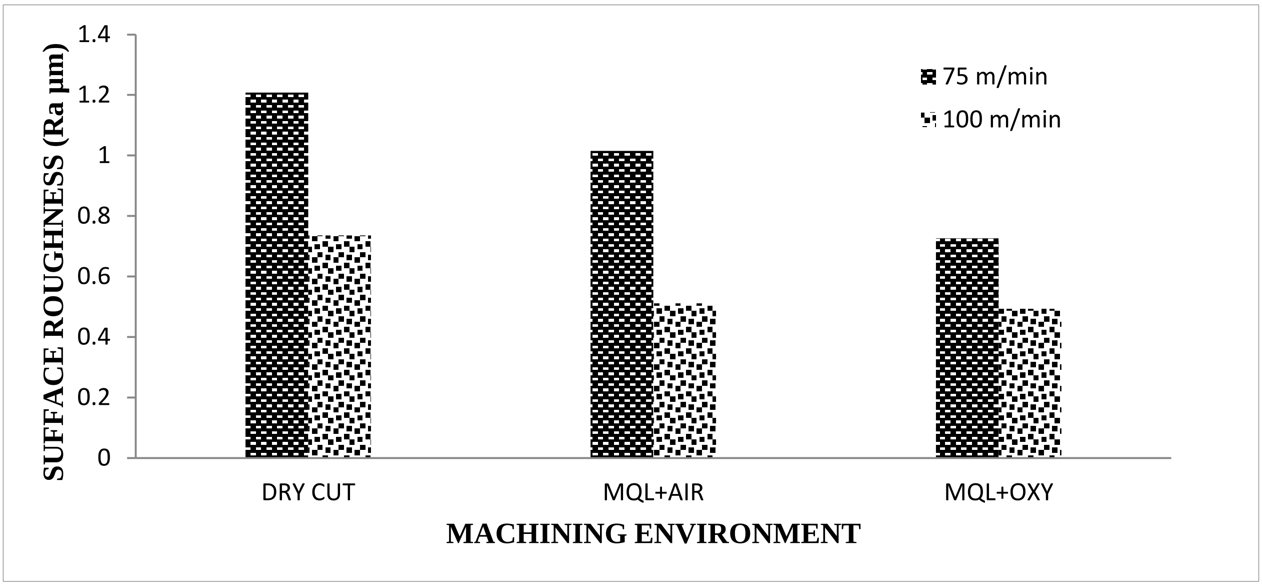


Figure 4: Surface roughness Ra (µm) vs. machining environment

3.3. Cutting force analysis

Parameters which influence the cutting forces are depth of cut, feed and cutting speed etc. In this section, the effect of machining environments viz., dry, MQL with air and MQL with oxygen on cutting force for the cutting speeds 75 and 100 m/min at a constant depth of cut of 0.5 mm and feed of 0.05 mm/rev is presented. Figure 5 shows the variation of cutting force results under different conditions. It is observed that cutting force for the MQL with oxygen is lowest as compared to the MQL with compressed air and dry cutting. Also the results show that cutting force reduction of 12%, 25% and 20% respectively for dry cut, MQL with air and MQL with oxygen as the cutting speed increases from 75 to 100 m/min. Subsequently increase in the cutting speed (Vc) decreases the cutting forces, which is attributed to thermal softening with rise in cutting temperature. When dry cut is compared with MQL conditions; reduction of cutting force is 2% for MQL with air and 35% for MQL with oxygen at low speed cutting. At low speeds, the temperature at the cutting point is equal or below the optimum temperature (shearing temperature). Hence, the deformation resistance of the work piece material at the cutting point will be more and thus cutting force is more. As speed is increased, cutting forces further decreases at the same percentage rate. This phenomenon can be explained to the extent of oxide layer formation and plastic deformation due to increase in the cutting temperature. But when MQL is applied with gases, temperature further decreases which makes it difficult for the tool to cut the material beyond the optimum temperature. This is the reason why MQL does not bring much reduction in the cutting force at low speed range[14].

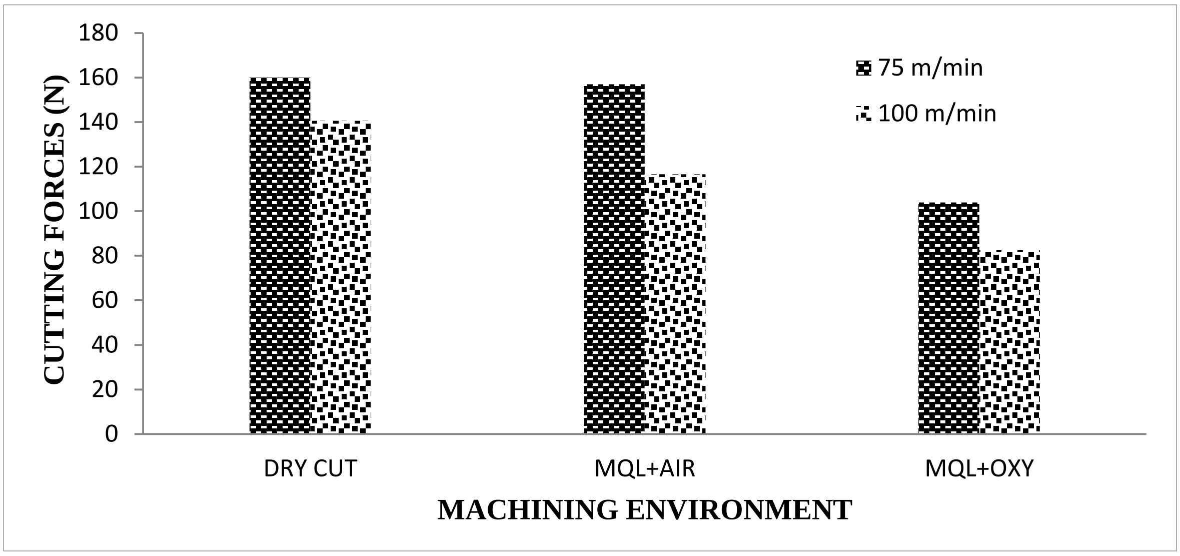


Figure 5: cutting forces (N) vs. machining environment

3.4 *Chip morphology*

Chip formation describes the pattern of surface roughness and surface integrity. Mechanism of chip formation with schematic diagram is illustrated in figure 6. Based on the experiments conducted under various MQL environments, respective chips are collected for the analysis. Chips obtained for MQL conditions were discontinuous and saw toothed for all the conditions except for dry cutting at 75 m/min. Saw toothed is main characteristic of hard to machine component.[15] Chips at low speed were discontinuous and rolled at one end and pointed at the other end as shown in figure 7(a). Top surface is jagged and rough appearance, due to shear mechanism and the bottom surface is smooth and shiny due to high contact pressure with rake face as well as frictional forces and high temperature [16].

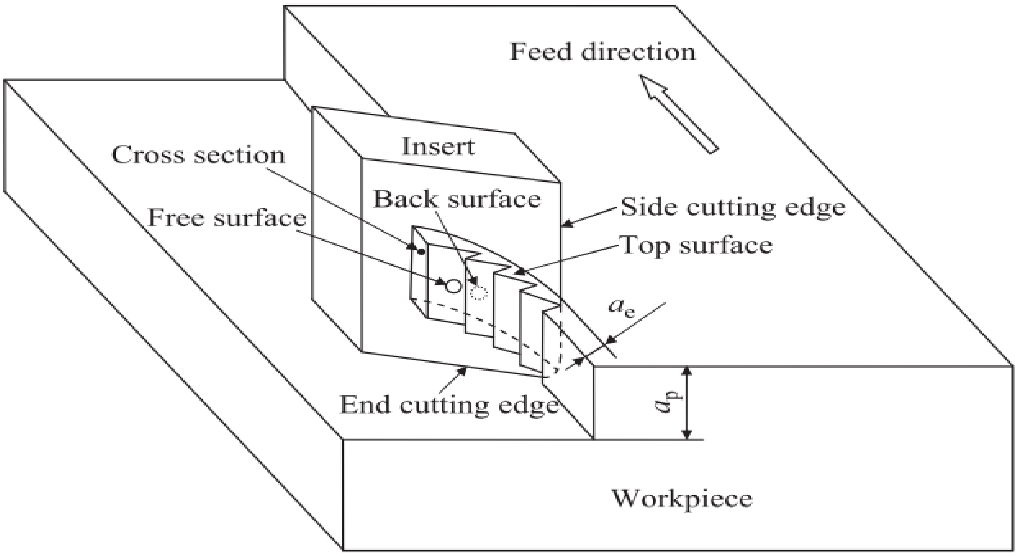


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Figure 6 3D schematic of chip formation in end milling (not up to the scale)[16]

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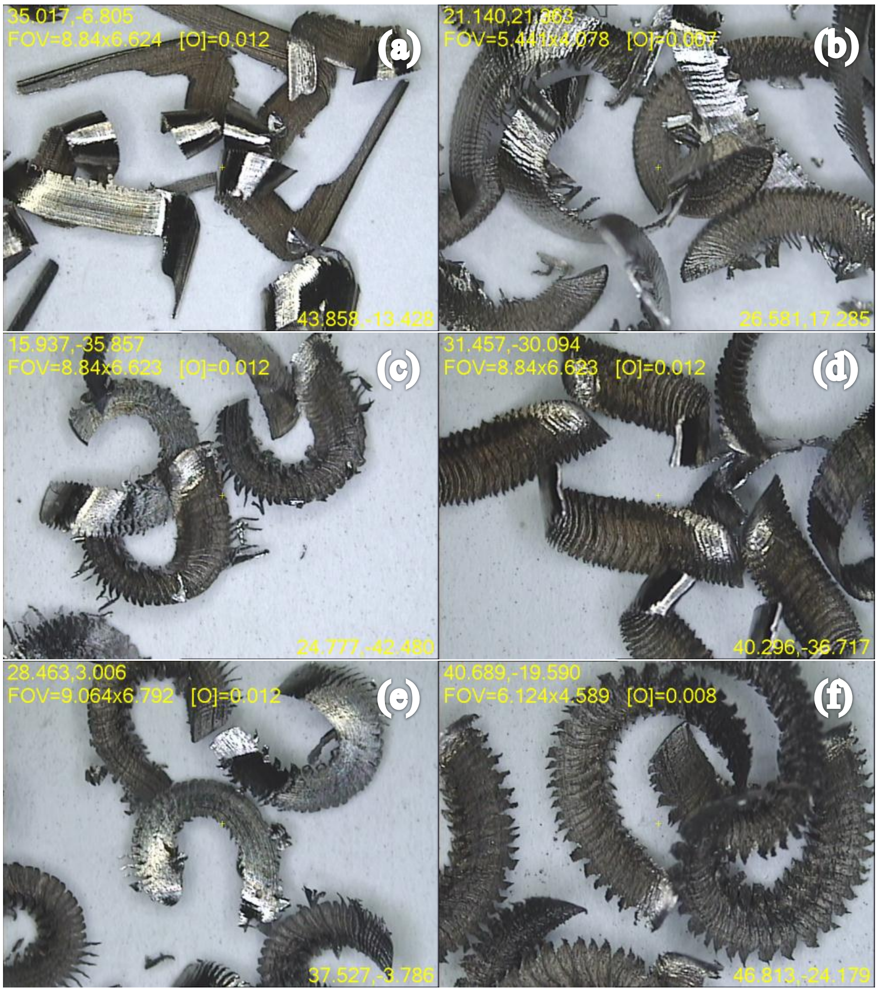

Figure 7. Chip morphology under various conditions (a) Dry cut 75m/min (b) Dry cut 100m/min (c) MQL with air 75 m/min (d) MQL with air 100 m/min (e) MQL with oxygen 75 m/min (f) MQL with oxygen 100 m/min.

4. Conclusions

Based on the results and discussions of the experimental investigation, the following conclusions can be obtained:

- MQL environment is benificial as compared to the dry cutting. Specially MQL with oxygen as carrier gas has resulted in less tool wear,cutting forces and better surface finish for the given machining parameters.
- There is no significant flank wear observed at low cutting speed except for dry cutting which shows severe crater wear.As speed increased to 100 m/min, tool subjected to more flank wear. i.e dry cut 32%, MQL with air 14% and MQL with oxygen 9%.
- Better surface finish is observed for MQL with oxygen.By facts surface roughness is influenced by the cutting speed, as speed increased from 75 to 100 m/min steep reduction in surface roughness was observed for each machining environment.Comparing dry cut with MQL conditons at low speed it is observed that 16% and 40% reduction in surface roughness for MQL with air and MQL with oxygen respectively.
- Cutting forces decreases for MQL conditons as compared with dry cut. While MQL with oxygen has observed lowest cutting forces.This phenomenon can be explained to the extent of

oxide layer formation and plastic deformation due to increase in the cutting temperature and low friction force at the tool-workpiece interface.

- Chip obtained from machining environment were discontinous and saw toothed. There was no significant variaton observed in chip morphology except for dry cutting at low speed which shows rolled at one end and pointed at the other end.

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