Performance Evaluation of PVD and CVD coated Inserts during End Milling with DRY and MQL condition

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CERTIFICATE

I hereby declare that the thesis entitled "**Performance Evaluation of PVD and CVD coated Inserts during End Milling with DRY and MQL condition**" is an authentic record of my work carried out as requirements for the award of the degree of **Master of Engineering** in **Production Engineering** at **Thapar University, Patiala** under the supervision of **Dr. Ajay Batish**, Professor, Mechanical Department, Thapar University, Patiala during July, 2013 to July, 2015. No part of the matter embodied in this report has been submitted to any other university or institute for the award of any degree.

Date: 13/July/2015

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It is certified that the above statement made by the student is correct to the best of my knowledge and belief.

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Dedicated to

Parents

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Abstract

The aim of this study is to evaluate the performance of PVD (TiAlN+TiN), (TiCN+TiN), and CVD (TiCN+Al_2O_3+TiN. 0315), (TiCN+Al_2O_3+TiN) coated inserts in end milling of EN–31 hardened die steel of 43± 1 HRC during dry and MQL machining. The experiments are carried out at two different stages. In first stage experiment is conducted at a fixed feed rate, depth of cut and varying cutting speed to measure the effect of cutting speed on cutting force, tool wear and surface roughness of different CVD and PVD coated inserts whereas in the second stage, the experiment is conducted under fixed cutting parameter i.e. (depth of cut, feed rate and cutting speed). The experiments are performed to compare the tool wear, cutting force and surface roughness of these coated inserts under dry and MQL condition. It is concluded that PVD inserts provide less cutting force, tool wear and surface roughness as compared to the CVD inserts because PVD inserts have a thin coating thickness as well as CVD inserts has a thick coating thickness, but PVD inserts experience catastrophic failure during cutting operation whereas CVD inserts have a capability for continuous machining under different machining. Tool wear also measure by SEM analysis. SEM (scanning electron microscope) analysis is used to analyze the adhesion and abrasion wear which occur during cutting operation of the cutting tool. MQL machining provides good result among all cutting conditions as compared to the dry condition. MQL machining has ability to work under high cutting speed as well as high depth of cut. It decreases the tool wear, cutting force and provide a good surface of the machined part.

Key words: Cutting forces; Cutting parameters; CVD coated inserts; Dry machining; MQL machining; PVD coated inserts; Surface roughness; Tool wear.

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Nomenclature

D	=	Diameter of tool
f	=	Feed per tooth
F	=	Feed rate
S	=	Spindle speed
Vc	=	Cutting speed
Z	=	Depth of cut
Ra	=	Arithmetic average
Rq	=	Root mean square
Rz	=	Five highest peak and Five deepest valley

CHAPTER 1
INTRODUCTION

1.1 Introduction

Milling is the machining process which is used to remove material from the work piece. When the cutter comes in contact with the work piece to machine the surface of the work piece, then tool marks remain on the surface of the work piece as well as there is also the gradual failure of cutting tools due to regular operation which decrease the tool life and also affects the surface finish. When the tool tip engaged with the workpiece certain forces act on the tool surface such as cutting forces, friction forces, and flow of chip on the tool which affect the tool life, surface finish and tool wear. These forces may reduce with increasing of positive rake angle, but no change in the clearance angle because when the rake angle increases the contact length of chip is the minimum which reduce cutting force as well as friction force. Milling process is widely used in the industries to produce mass product. During operation, the cutting temperature is increased which melt the tooltip and also some chip material stick on the front face of the tool due to high temperature. For solving this problem, cutting fluids are used during cutting which help to control the cutting temperature by cooling and lubrication on the cutting surface. The main function of the cutting fluid is to flush away the metal chips from the workpiece surface and provide cooling on the interface of the tool and the surface of the workpiece which increases the surface finish of the material and tool life of the tool by reducing cutting forces. It also reduces the occurrence of built up edge and minimize the tendency of chip adhesion as well as chip pressure to the tool tip. There are many advantages of using the cutting fluid in the production shop such as it provide cooling between the tool and workpiece surface, reduce friction forces which act at the interface of the chip and tool surface. But on the other side, it also has some drawback which is related to health (pyrosis, fungal infection, skin related problem and asthama, dermatitis), environment, cost and part performance. To overcome the problem of the excessive use of cutting fluid, Minimum Quantity Lubrication (MQL) is preferred to use in place of flood lubrication because it use 40 – 47 ml/hr and 20 -25 ml/hr which decreases the cost of the part and increase quality of the product. In MQL, coolant oil is mixed with high pressure due to machining. MQL have many advantages over the flood lubrication, coolant face difficulty to reach on the area of the cutting zone, whereas in MQL, it easily reaches on the cutting zone area due to the mixture of high pressure air and liquid. MQL machining also gives good result against the dry machining as well as flood lubrication as in high speed machining, dry machining is mainly preferred because it generates the high cutting temperature due to which workpiece get heated and become soften which increase the surface finish, whereas in flood lubrication machining, coolant unable to reach or cutter through away the coolant from the area of the cutting zone but MQL due to high pressure it easily reach the cutting zone area and able to minimize the cutting force as well as tool wear. In this present investigation EN-31 material is used for the experiment due to its high resisting nature against the wear. Tool wear is directly affecting the tool life of the tool which affects the productivity. For increasing the productivity and surface finish of the product, two PVD and two CVD multilayer inserts are used in this experiment and machining these inserts with MQL and Dry lubrication condition to measure the cutting forces, surface finish and tool wear and compare the performance. The aim of this research is to perform an experiment of different coated insert in dry and MQL lubrication in order to measure the impact of cutting speed values on the surface finish, cutting forces and tool wear.

1.2 Milling Machine

The process of removing the unwanted material from the work piece to get the desired shape and size. Milling process is mainly used for the mass or bulk production, if any industries want to do accurate machining then they used milling. It is used to manufacture complex shape geometry. In the milling process, the cutter, having multiple teeth rotate on the surface of the work piece to remove the material. When the cutter engaged with the work piece, it increases the cutting temperature as well as cutting forces which act at the interface of the tool and work piece due to this catastrophic failure occur.

Milling machines can be generally categorized as: Vertical milling machine and Horizontal milling machine which are discussed below.

1.2.1 Vertical Milling Machine

In Vertical milling machine, tool axis is perpendicular to the workpiece axis. In this machine spindle move vertically whereas table moves in X and Y axis direction. It has a heavy arm, which supports the spindle. This arm is established at a certain distance from the column as shown in Fig. 1.1.

Figure 1.1: CNC milling machine

1.2.2 Horizontal Milling Machine

In Horizontal milling machine, the axis of the tool are parallel to the surface of the work table as shown in Fig. 1.2. It is useful for small production and it is not suitable for heavy duty work because it slows down the machine.

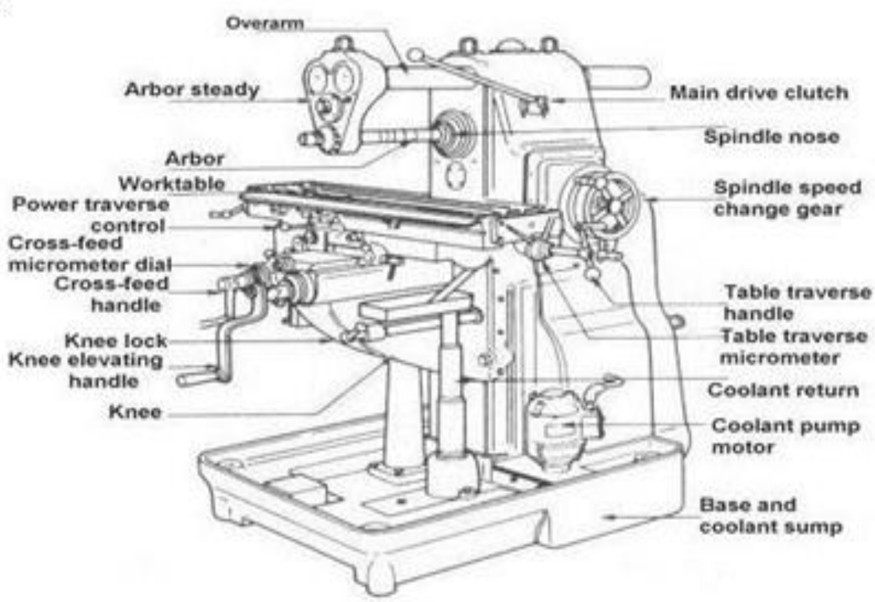


Figure 1.2: Horizontal milling machine [W.1]

1.3 Milling Cutter

Milling machine offers a large number of special products with the help of the milling cutter. The cutter has a quality to produce high amount of chips in one revolution. There are wide ranges of milling cutters as shown below.

1.3.1 Plan cutters

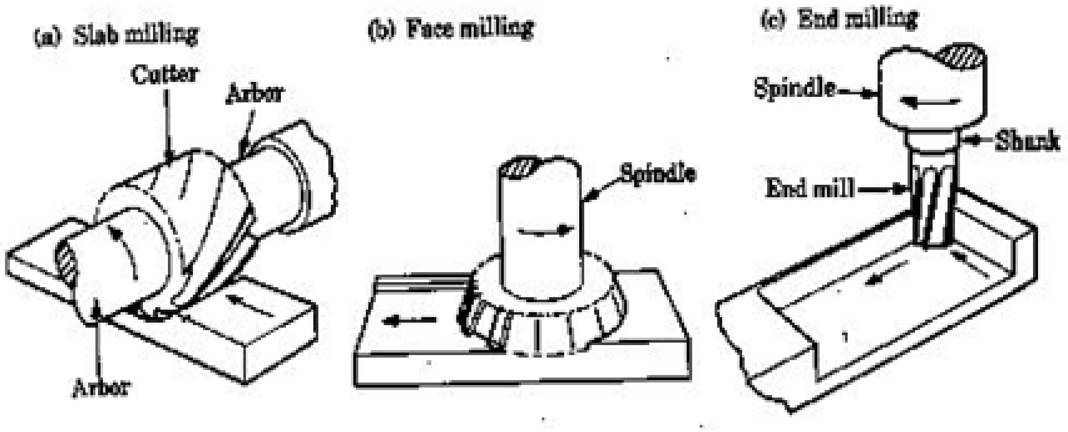
It is also called slab milling. It has cylindrical in shape, having a cutting tooth on the periphery as shown in Fig. 1.3 (a). There are mainly two types of cutting cutter such as light duty slab milling and heavy duty slab milling. In light duty slab milling, it has mainly face width which is mainly small and have a large number of teeth which makes the cutter strong.

1.3.2 Side and Face mill cutter

This type of cutter is cutting edge on both sides as well as it has a face like slab milling cutter as shown in Fig. 1.3 (b). It can be used as a slot milling as well as side milling.

1.3.3 End mill

End mill mainly used in the vertical axis milling machine. These are used for machining slots, keyway and pocket, where other types of the milling cutter cannot be used as shown in Fig. 1.3 (c). In End mill, it always remembers that the depth of cut should always half of the diameter of the cutter. The cutting edge of the end mill moves through the length of the cut as well as radially move up to a certain position. HSS cutting tools are generally recommended for the end milling.



(a) (b) (c)

Figure 1.3: (a) Slab milling (b) face milling (c) End milling [W.2]

1.4 Process Parameters in Milling

The operating conditions in the case of the milling operation are as follows

1) **Cutting Speed**: It is defined as the peripheral speed of the cutter. It is given in the equation (1.1).

$$V = \frac{\pi DN}{1000} \quad (1.1)$$

Where,

V= cutting speed, m/min

D = diameter of cutter, mm

N = rotational speed of cutter in rpm.

Proper selection of cutting speed depends on the properties of the material being cut, diameter and life of cutter, number of cutter teeth, feed, depth of cut as well as width of cut (or cutter) and use of coolant.

2) **Feed per tooth**: It is the linear distance covered by the tool, when one tooth is engaged with the workpiece during the cut. It is expressed in mm. The feed per tooth can be determined from the Eq. (1.2).

$$f_1 = \frac{f}{NZ} \text{ mm} \tag{1.2}$$

Where,

f_1 = feed per tooth, mm

f = feed rate, mm/min

Z = number of teeth of the cutter periphery

N = rpm of the cutter

3) **Feed per cutter revolution:** It is defined as tool covered the distance during one revolution. It is used to calculate the finishing capability of the face mill as well as calculate the feed by using the Eq. (1.3). It is expressed in mm/rev of the cutter. It is related to feed per tooth as:

$$f_2 = f_1 Z \text{ mm/rev} \tag{1.3}$$

Where,

f_2 = feed per cutter revolution, mm/rev

4) **Depth of Cut:** It is defined as the amount of material removed from the workpiece in a single cut. Axial depth is for face milling whereas radial depth is for peripheral milling. It is expressed in mm.

5) **Width of cut**: It is defined as the amount of workpiece surface is covered by the tool.

1.5 Mechanism of Milling

1.5.1 Chip Formation

In the material removal process, the material is removed from the rake face. As the cutting tool engaged with workpiece then metal is compressed first elastic, then plastic as shown in Fig.

1.4. This region is known as shear zone. The removal of the material is dependent upon the cutting conditions and deformed the chip which flow over the tool face. Due to the relative motion between the chip and the tool, friction forces are acting on the interface of the chip as well tool and chip again get deformed. This is called secondary deformation. If tool travels onward, then chip of the tool passes over the shear plan region. If the workpiece is ductile then no fracture will take place during cutting and chip form continuous ribbon like structure, but if the workpiece material is brittle, then the material break or deform during the cutting operation and discontinuous chips will be from. As the tool engage to the workpiece, cutting forces also acted on the tool in the three direction i.e. Radial force, axial force and tangential force.

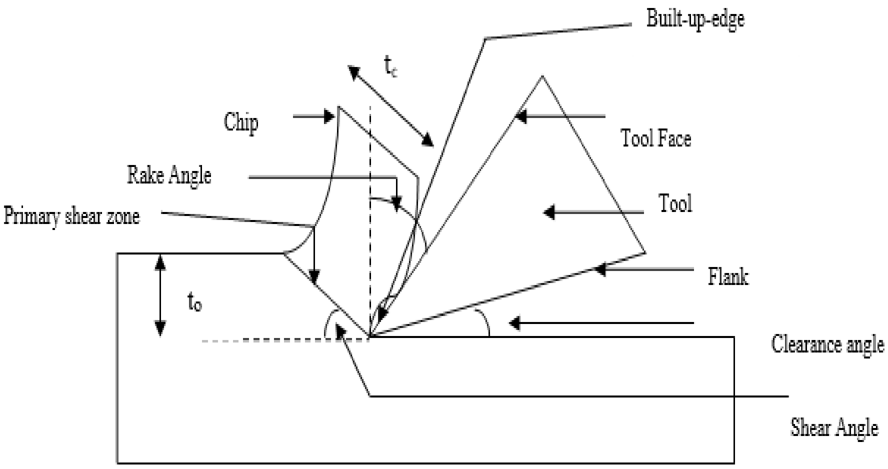


Figure 1.4: Geometry of chip creation during cutting

1.5.2 Thermal Aspect

Power consumed during cutting operation converted into heat, which help to increase the temperature in the cutting zone. Due to increase in temperature, excessive heat is generated which affects the strength of the tool, hardness and wear resistance of the cutting tool. It can also create the dimensional inaccuracy on the part and also making the path to be difficult in machining. This affects the properties of the workpiece material during cutting as well as also affect the life of the tool. Heat dissipation during plastic deformation in the primary zone due to the shearing as well as the contrast of chip and tool**.**

There are three types of zone of metal cutting such as:

1) **Primary Zone:** It is also known as shear zone. In this zone maximum heat is generated due to the internal friction and plastic deformation. This process is rapid as well as continuous and it generates 65 to 70% heat on the cutting zone.

2) **Secondary Zone:** This region is known as friction region. Friction is generated due to the contact of chip and tool surface. Heat is generated at 15 to 25 % due to the relative motion of the chip and tool.

3) **Tertiary Zone:** In this zone the friction occurs between the tool and workpiece which generates 10% heat.

1.5.3 Tool Wear

There are basic types of wear that affect a cutting tool.

1. **Abrasion wears:** When there is a relative motion between two surfaces and asperities are present between the surfaces, then some material is removed from the surfaces. If one surface is hard and other is soft surface, then less material is removed from the hard surface and more material is removed from the soft surface. This happens in metal cutting when built-up-edge will not stable so it break down the hard particle and spread.
2. **Adhesion wears:** This wear occurs due to the high amount of normal shear stress act on the tool. When built-up-edge has appeared on the tool surface and try to tear out the built-up-edge from the tool surface then it also tear out some tool material. This wear occurs due to the plastic deformation and friction, high temperature in cutting zone.
3. **Diffusion wears:** It is caused by a displacement of atoms in the metallic crystal of the cutting element from one lattice point to another and due to this wear gradual deformation occurs on the tool surface. It is dependent upon the intermittent temperature and chemical affinity. If the tool is diamond and the workpiece is ferrous then diffusion wear is more due to high affinity.

Wear is evident in two places on a tool.

- **Crater wears:** Crater wear is mainly occurring on the rake face and is more or less circular. It takes place on the face of the tool at a short distance from the tool edge by the action of the chip particles flowing over the face as shown in Fig. 1.5(i). Crater wear is formed due to the friction between the tool and the metal chip. It is a temperature dependent phenomenon.

This wear occurs mainly due to the diffusion along with abrasion. Length of the crater has been always same for the chip contact length.

- **Flank wear:** Flank wear is mainly occurring on the clearance or the flank face of the tool. It happens due to the work hardening which will increase friction, reduce surface texture. The main reason of the flank wear is abrasion and adhesion. This has generated due to the friction between the machined surface and the tool flank surface. This wear is generated in three zones as shown in Fig. 1.5(ii).

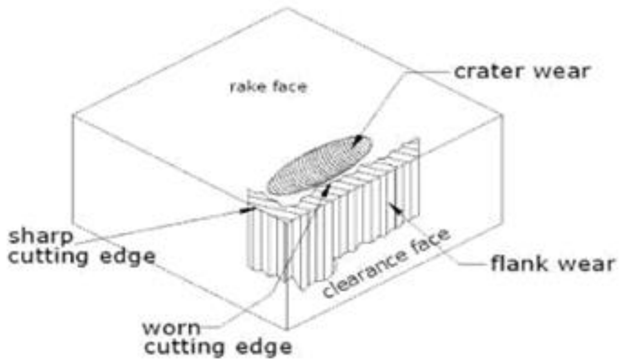


Figure 1.5: (i) Crater wear (ii) Flank wear [W.3]

Tool changing criteria for various tool after wear.

For HSS

(i) Catastrophic failure: It is not predictable or regular failure.

(ii) $(V_B)_{mg} = 0.3$ mm

(iii) $(V_B)_{mg} = 0.6$ mm

For Carbide

(i) Catastrophic failure: It is not regular failure

(ii) $(V_B)_{mg} = 0.3$ mm

(iii) $(V_B)_{mg} = 0.6$ mm

(iv) $Kt = 0.06 + 0.3f$

Where f = feed rate mm/min

Tool Life

During cutting, when the tool comes in contact with the workpiece then the cutting edge of the tool gradually wear out and doesn't able to perform. After a certain time, a tool has lost its cutting ability and its life is over. If machining is continued the tool should be replaced by a new tool. Tool life play an important role to evaluate the cost of machining of any product by their machinability. It is defined as the time interval between the consecutive resharpening between the tools perform satisfactorily. Eq. (1.4) shows the formula of tool life which was given by the Taylor.

These are following common method of measuring the tool life such as:

- Machine Time: It is the elapsed time operation of the machine tool.
- Actual Cutting Time: Time during which the tool actually cuts.
- Average length of the cut per tool.
- The average number of the parts machined per tool.
- Cutting speed at which actual time obtained.

Tool Life Equation

$$VT^n = C \qquad (1.4)$$

Where

V = cutting speed (m/min)

T = time (min)

F = feed rate (mm/rev)

n = exponent that depends on cutting condition

1.6 Cutting Fluids

Cutting fluid is used to control the cutting temperature by cooling and lubrications. The main function of the cutting fluid is to flush away the chips and metal particles from the surface of the workpiece. Cutting fluids increase the surface finish of the part and tool life of the tool as well as decrease the occurrence of built up edge and tool wear.

Advantages

- ✓ It provides cooling to the interface of the tool and workpiece.
- ✓ It reduces friction which is generated due to sliding of chips on the tool surface.
- ✓ It flush away the chip particles from the cutting zone.
- ✓ It helps to increase the surface finish of the machined part and reduce tool wear.
- ✓ Permit to run the tool at higher cutting speeds.

Disadvantages

- ✓ Cutting fluid creates a health related issues such as (pyrosis, fungal infection, skin diseases and dermatitis)
- ✓ Cutting fluid also effect environment.
- ✓ High cost is needed for applying the cutting fluid.
- ✓ Cutting fluid can only reuse after filtering the used fluid which increases the machining cost.

The main function of a cutting fluid is to control heat, cutting forces and flush away the chip from the cutting zone region. This is followed mechanisms are done.

- **The Cooling Mechanism:** It is used to control the cutting temperature through cooling. The main function of the cutting fluid is flush away the chips and metal fins from the workpiece surface and the tool interface.
- **The lubrication Mechanism:** It reduces the friction between the chip and tool which is generated due to the relative motion. The viscosity of a prevailing layer of fluid can play an important role in regulating friction, when the forces are relatively low.

Cutting Fluid Application strategies

The principal methods of cutting application include:

- **Flood application of fluid:** In this application, lubrication is applied to the cutting zone to minimize the cutting forces. It helps to reduce the cutting forces and cutting temperature, which generate during cutting operation. This application provides a good surface finish and reduce tool wear.

- **Jet application of fluid:** In this application, cutting fluid is directly injected on the workpiece of the cutting zone. This fluid may be liquid or gas and it is injected in the form of fine jet under pressure (up to 4MPa). It gives better results than flood application because coolant, easily reaches cutting zone during cutting operation which gives better cutting performance and good surface finish.
- **Mist application of fluid:** In mist application, very small droplets of the cutting fluids is dissolved in a gaseous medium. It is the mixture of air and water and applied in the cutting region. There are various advantages of this application such as
  - ❖ Due to large surface to volume ratio, there is a quick vaporization of the droplet.
  - ❖ It improves the penetration ability of the cutting fluid due to the small size of the particles.
  - ❖ In mist application, less cutting fluid is used as compared to the flooding
  - ❖ Due to compressed air, chip flow away from the cutting zone.
  - ❖ During cutting operation, it is noted that mist application generally gives low flank wear and better surface finish as well as it also effective at higher federate.

Types of Cutting Fluids

There are three types of cutting fluids which are mainly used. These are as follows:

- **Water based emulsions:** In this type, pure water is used as the cutting fluid due to its high specific heat carrying capacity. It has low viscosity which increases the flow rate during cutting operation. Although it has corrosive nature, but it easily diluted with any other concentrated oil to get the desired concentration.
- **Straight mineral oils:** These are pure mineral oil without adding any other additives. It mainly used due to lubrication as well as to prevent rust. Beside this it has low in cost and chemical stable.
- **Mineral oils with Additives (Neat Oil):** These oils are mainly used those places where machining condition is difficult. This oil known as neat oil. These additives mainly used for improving the load carrying capacity and chemical activity. Fatty oil is mainly used for adding the load carrying capacity, whereas extreme pressure additives are used in the most difficult machining situation.

1.7 Organization of Thesis

The thesis is divided into six chapters. These are as follows:

Chapter 1 provides the introduction of the thesis, in which milling process, process parameter in milling, chip formation, thermal aspect, tool wear and cutting fluid are explained. Mostly chip formation generates heat on the cutting zone during cutting operation. This excess heat reduces the tool life and increase the roughness of the machined surface. Cutting fluid is used to transfer the generated cutting heat during cutting operation as well as reduce the cutting temperature during cutting operation.

Chapter 2 covers the literature survey related to the end milling process under different lubrication conditions such as flood, dry, MQL and explain the effect of these different lubrication conditions on the cutting force, surface roughness and tool wear.

Chapter 3 this chapter describes the material and methodology which are used in the present experimental study such as tool geometry, workpiece, milling machine, fabricated MQL setup and measurement of cutting force, surface roughness and tool wear. Dynamometer is used to measure the cutting force which is generated during cutting. Surface roughness tester is used for measuring the surface roughness of the machined surface and measuring microscope as well as SEM is used for measuring the tool wear.

Chapter 4 this chapter shows the evaluation of the performance of PVD and CVD under dry and MQL condition during different cutting parameter in milling. In this chapter, measure the cutting forces, tool wear and surface roughness of individual carbide coated inserts. Compare the performance of both PVD inserts, PVD and CVD inserts as well as two CVD inserts on different cutting condition and measure the effect of process parameter on cutting force, tool wear, and surface finish. It also covers the discussion of the result on the performance of PVD and CVD inserts during different condition such as dry and MQL condition.

Chapter 5 gives the conclusion of the present experimental work which is drawn on the basis of the experimental results.

CHAPTER 2

LITERATURE SURVEY

2.1 Introduction

There are many research had done in the area of end milling, having different machining condition and tool geometry, but their aim was to minimize cutting force, surface roughness and tool wear. They all took different parameters as well as cooling condition to achieve the target. The literature review relating to the machine capability calculation of advanced materials by end milling has been divided into three sections.

2.2 Literature Review

2.2.1 Cutting Forces

Toh [2003] performed the experiment on AISI H13 workpiece and tungsten carbide to analyze the surface topography, surface texture and surface roughness, cutting forces and vibration during milling under dry condition in which high pressure air nozzle is also injected during cutting. This study focused on the different cutter path approaches to know the effect of axial depth of cut. It observed that high material removal achieved in less cutting time.

Sun et al. [2006] performed the experimental study under three cutting condition such as dry condition, flood cooling, MQL technology on titanium alloy during milling operation and observe that less cutting force were achieved in MQL machining and also study the effect of federate on cutting forces. Federate acts as a significant factor to reduce cutting force. It was concluded that as the cutting speed increases, tool life decreases, but in MQL, tool life was increasing as the cutting speed increases. Normally the radial depth of cut was increased tool life in all coolant conditions, but MQL condition provides better results over the other coolant method.

Reddy and Rao [2007] investigated the comparison study to evaluate the performance of a solid coated (TiAlN) carbide on AISI 1045 workpiece during wet and solid lubrication under end milling to know the effect of machining parameters such as radial rake angle, nose radius, feed rate, and cutting speed. Results show the effect of machining parameters was significant during cutting operation, whereas their interaction had not effect on the tool as well as the workpiece. Graphite powder is used to increase the performance of machining because it reduces the friction force as well as heat generated between the tool tip and the surface of the workpiece. It concluded that solid lubrication help to reduce cutting forces and chip thickness ratios such as contact area of chip and tool as compared to the wet condition.

Yuan et al. [2011] performed the experiment on uncoated cemented carbide inserts and workpiece of Ti-6Al-4V alloy to study the effect of different coolant conditions such as dry condition, flood cooling and MQL without high pressure air as well as MQL with high pressure air on the cutting force and concluded that less cutting force was achieved by the MQL (with cooling condition) as compared to the other condition. In MQL (with cooling condition), short chip formed. Hence it was proved that MQL (with cooling air) was a good substitute for other old-fashioned techniques.

Boswell and Islam [2012] performed the experiment during different coolant condition i.e. Dry, flood, cooled air, MQL without high pressure air and MQL with high pressure air under varying cutting speed at fixed depth of cut and fixed federate in aluminum. It concluded that less cutting force, good surface finish was achieved during MQL (without cooling air) and MQL (with cooling air) than flood cooling. In cold air, very small amount of vegetable oil was used, so it was not dry processed. It was a little bit similar to the sustainable.

Hao et al. [2012] investigated the performance of PVD (TiAlN) carbide tool in Inconnel 718 during dry machining when operated in turning machine. In this study, they vary the cutting speed with fixed feed rate as well as depth of cut and measure the cutting forces and record the cutting signal in three directions through charge amplification and data acquisition card, and cutting temperature. It was concluded that as cutting forces increases with increase of the cutting speed.

Premnath et al. [2012] performed the experiments on tungsten carbide and hybrid composite during dry machining under milling condition. It studied the effect of weight of the weight fraction of Al2O3 and machining parameters such as cutting speed, depth of cut, federate on the surface roughness as well as cutting force. It concluded that less cutting force and surface roughness were achieved during low federate and high spindle speed, but some micro scratches as well as field marks were shown at higher feed rate machining. Flank wear was noticed due to high pressure generated at the tool-workpiece interface.

Cao et al. [2013] performed the experiment on the AISI/P20 workpiece with ball-end mill cutter to know the effect the cutter eccentricity and angular rotation of the cutter on cutting force and rotational angle. Results show that cutter eccentricity affects the cutting force due to the chip thickness, whereas in angular location, cutting force was affected by the rotation angle.

Niu et al. [2013] evaluated the performance PVD-(TiN+TiAlN) and CVD (TiN+Al2O3+TiCN) coated tool inserts on two different titanium alloys such as TC11 and TC17 under face milling and measured the effect of the machining parameters on cutting forces, surface roughness and chips morphology as well wear mechanism. It was concluded that TC17 alloy was more difficult-to-cut material than TC11 alloy. In PVD coated inserts, crater wear and chipping were the dominant failure where as In CVD coated insert, flank wear and breakage.

Pathak et al. [2013] investigated the effect of two Al-alloys having a composition such as Al-1Fe-1V-1Si and Al-2Fe-1V-1Si during end milling operation to measure the cutting forces, mainly radial forces at different cutting conditions such as depth of cut, cutting speed as well as feed rate to evaluate the effect of these cutting forces. It concluded that as the cutting speed increases, then it reduces cutting force. Mostly cutting forces increases with feed rate and depth of cut. Chip thickness also depends on the increase of cutting force. During experiment, it was noticed the effect of cutting force by the depth of cut as compare to the feed rate and cutting speed.

Tian et al. [2013] performed a series of milling tests on Inconel 718 with ceramic tools during face milling in both down-milling and up-milling to measure the influence of cutting speed on cutting force and tool wear. It concluded that the resultant cutting forces first decreases, but after some time, it increases with the cutting speed. Under relatively lower cutting speeds (600 and 1,000 m/min), the leading wear patterns were notching. But after 1400 m/min or more cutting speed than notching decreases and flank wear leads the wear pattern. In general, at the same cutting speed, flaking on the front rack of the tool and notching on the flank face were more severe in down-milling operation than that in up-milling operation with the same metal removal volume. However, the surface roughness values for down milling were lower than that for up-milling.

2.2.2 Surface Roughness

Toh [2003] also analyze the surface topography, surface texture and surface roughness. During the experiment, it was noticed that improves offset strategy increase the surface roughness value of the workpiece as well as up milling orientation of the tool, provides a better surface finish as compared to down milling. It was concluded that raster strategy provides lower surface roughness value as compared to the single direction raster down milling strategy.

Ekinovi et al. [2007] performed the experiment to investigate the quality of the machined surface during high speed cutting technologies and conventional turning under different material, hardness as well as machinability index. The result shows that high speed technologies provide better result than conventional tuning. It also noticed during experiment that some new tools which was used in conventional turning also used in high speed applications.

Reddy and Rao [2007] also investigated the surface roughness of the machined part as same cutting and lubrication condition under same tool and the workpiece. It was concluded that solid lubrication provides a good surface finish as compared to the wet condition.

Bruni et al. [2008] performed a machining test under different cutting conditions (dry, wet and MQL) on AISI 420B stainless steel. Results show that Ra value decreases as cutting time increases under wet cutting, but in MQL condition, same or less Ra value was achieved as well as it also reduces the flank wear during cutting at high speed. During experiments, it was noticed that there was no effect of speed variation on the surface of the machined part. For producing Ra value, it used MRR and ANN model. This model provides good results as the number of trials increased.

Siller et al. [2009] investigated the effect of particular carbide PVD AlCrN coating tool on hardened steel in the face milling operation and measure the surface roughness, tool wear and flatness of the surface to analyze the best operating conditions. It concluded that the minimum value of the surface roughness was obtained from the experiment with a satisfactory tool life.

Tosun and Huseyinoglu [2010] investigated the influence of the machining parameters i.e. Federate and spindle speed under MQL and conventional lubrication during face milling. The flow rates of MQL coolant and conventional coolant were set at 5 and 1000 ml/min. The conventional coolant was containing boron oil and water solution, whereas MQL coolant was contained the compressed air and less quantity of cutting fluid which deliver on the tool and workpiece interface. The result shows that if cutting speed increase then surface roughness will be decreased and if there was a variation in feed rate then it also effect the spindle speed. As spindle speed increases with decreases of the feed rate then good surface finish achieved. There were also the some effects of cooling techniques and cutting tool on the surface roughness. Different tool material varies the surface roughness and it was found that WC-Co mills provide better surface finish compared to the TiCN and HSS mills. When the spindle speed was higher than the MQL cutting gives a better surface finish as compared to the conventional cooling and vice versa.

Zhang and Li. [2010] proposed the relationship among tool wear, surface topography and surface roughness as well as find the optimal value of the flank wear which affect the tool life and surface roughness during finish milling process. It performed the experiment by layer by layer cutting of the workpiece in the interval of 2, 4, 6, 8, 10 min and analysis the tool wear and surface roughness after cutting each layer. It analysis with the result that first two layers have less tool wear and surface roughness, but last two layers have start rapid tool wear and surface roughness. They concluded that surface roughness increase with the increase of tool wear. Tool wear and flank wear increase as the cutting time increases.

Ding et al. [2011] performed a comparative study on AISI H13 steel by using different type of insert geometry such as parallelogram and round shaped insert to find the surface roughness and residual stress during the end milling operation. In this experiment they considered four cutting parameters such as cutting speed, feed, radial depth of cut and axial depth. During the experiment they observed that in parallelogram insert, axial depth of cut had a powerful effect on the surface roughness as well as generates more residual stress, whereas in round insert, feed was a leading parameter which affects the surface roughness and less compressive forces were generated. It concluded that round insert gives a good surface finish as compared to the parallelogram insert so round insert was suitable for the finish milling process whereas parallelogram insert was suitable for the rough milling process.

Ozcelik et al. [2011] performed the experiment to evaluate the performance of the inserts on AISI workpiece under dry and wet machining during end milling operation. The experiment was performed in two stages; in first experiment, it fixed the federate, depth of cut, and varying speeds whereas, in second experiment, it fixed the cutting speed and depth of cut at varying federate. In this study, they measure the tool wear, milling force component as well as surface roughness under these operating conditions and compare the results. It concluded that dry cutting gives the best result of the tool wear over semisynthetic cutting fluid as compared to the presence of cutting fluid in milling machining.

Yuan et al. [2011] also observed the surface roughness on the same cutting parameter as well as lubrication condition and concluded that less cutting force was achieved by the MQL (with cooling condition) as compared to the other condition. In MQL (with cooling condition), short chip formed. Hence it was proved that MQL (with cooling air) was a good substitute for other old-fashioned techniques.

Boswell and Islam [2012] performed the experiment during different coolant condition i.e. Dry, flood, cooled air, MQL without high pressure air and MQL with high pressure air under varying cutting speed at fixed depth of cut and fixed federate in aluminum. It concluded that less cutting force, good surface finish was achieved during MQL (without cooling air) and MQL (with cooling air) than flood cooling. In cold air, very small amount of vegetable oil was used, so it was not dry processed. It was a little bit similar to the sustainable.

Premnath et al. [2012] performed the experiments on tungsten carbide and hybrid composite during dry machining under milling condition. It studied the effect of weight of the weight fraction of Al2O3 and machining parameters such as cutting speed, depth of cut, federate on the surface roughness as well as cutting force. It concluded that less cutting force and surface roughness were achieved during low federate and high spindle speed, but some micro scratches as well as field marks were shown at higher feed rate machining. Flank wear was noticed due to high pressure generated at the tool workpiece interface.

Zhang et al. [2012] investigated the micro structural variation and micro hardness acting on the adjacent surface by using different cutting parameter in the milling operation of AISI H13 steel workpiece and the PVD coated tool. The objective of this study to observe the formation of the white layer on the machine surface comparatively on the chip surface. In this study it was found that hook shape profile was generated at the top of the surface and which was hard enough, but as the depth of cut increases up to 25 μm then micro hardness became smaller by the reason of micro gradient get flatter which show the less gradual plastic deformation as the depth increases. It concluded that the shapes of the micro hardness which occur underneath of the machined surface were strong interacting to the micro structural variation which was appearing on the adjoining surface.

Fan et al. [2013] measured the surface roughness during an investigation under fixed cutting conditions and analyzed the machined surface morphology, as well as the effect of built-up-edge, and chip side flow on the surface quality. It performed the experiment in which cutting speed was varied such as 25, 35, and 45 m/min at fixed depth of cut as well as feed rate (a_p = 1 mm, f = 0.12 mm/rev). During experiment, it was observed that at high cutting speed at Vc = 45 m/min, there was plastic deformation and burr formation in the machined surface which led to surface breakage, but when cutting speed was 35 m/min, smooth machine surface was obtained.

Niu et al. [2013] evaluated the performance PVD-(TiN+TiAlN) and CVD (TiN+Al_2O_3+TiCN) coated tool inserts on two different titanium alloys such as TC11 and TC17 under face milling and measured the effect of the machining parameters on cutting forces, surface roughness and chips morphology as well wear mechanism. It was concluded that TC17 alloy was more difficult-to-cut material than TC11 alloy. In PVD coated inserts, crater wear and chipping were the dominant failure where as In CVD coated insert, flank wear and breakage.

Pathak et al. [2013] investigated the effect of two Al-alloys having a composition such as Al-1Fe-1V-1Si and Al-2Fe-1V-1Si during end milling operation to measure the cutting forces, mainly radial forces at different cutting conditions such as depth of cut, cutting speed as well as feed rate to evaluate the effect of these cutting forces or parameters on the surface roughness by using a surface roughness tester. It concluded that as the cutting speed increases, then it reduces cutting force. Mostly cutting forces increases with feed rate and depth of cut. Chip thickness also depends on the increase of cutting force and effect the surface finish as well as the workpiece. During experiment, it was noticed the effect of cutting force by the depth of cut as compare to the feed rate and cutting speed.

Cai et al. [2014] performed the experiment to investigate the performance of solid cemented carbide and AlTiN-TiCN-TiN coatings on Inconnel 718 in end milling under dry condition with different cutting parameters and measures the effects of cutting parameters on the surface integrity, such as surface topography, surface roughness *Ra*, and residual stresses and also analyzed the changes of microstructure as well as microhardness. Results show that surface roughness increased, if cutting speed increased from 20-80 m/min but at cutting speed= 110 m/min, good finish was achieved as same at 20 m/min surface. As a cutting speed was increased to 20-80 m/min, then the surface of the machined part gets poorer. Feed rate also affects the surface of the machined parts. Residual stress was generated with the tool in both direction i.e. Perpendicular as well as parallel according to the feed. Grain boundary also forms in the cutting direction at 80-110 m/min, whereas no significant effect at 50 m/min.

2.2.3 Tool Wear

Jawaid et al. [2000] investigated the performance of PVD/TiN and CVD/TiCN+Al_2O_3 coated carbide tool on Inconel 718 during face milling under the coolant (mineral oil with emulsion) and measures tool life of the carbide inserts. During experiment, it was noticed that the effect of cutting speed and federate was negligible. The result showed that the performance of CVD coated tool was better than PVD coated tool for all the cutting condition apart from the cutting parameter such as f = 0.12 mm/tooth and Vc = 50 m/min. CVD tool was discontinued due to the premature failure of one insert at this special condition. Chip flow was not noticed on the front face of the tool because the chamfer face creates a sufficient rake phase. The PVD coated tool gives poor performance due to the sharp cutting edges which delay in cutting, whereas in CVD coated tools, there was slightly rounded cutting edge which gives priority to the cutting process.

Braghini et al. [2001] performed the experiment on PCBN and indexible inserts coated with cemented carbide i.e. TiN under dry condition during end milling on die steel such as AISI H13, DIN 1.2713, AISI D6 at 48-56 HRC. In this studied it measures the wear by using SEM analysis. The result shows that PCBN tool achieved less flank wear which increase the tool life than carbide inserts at cutting speed (60-100 m/min) whereas carbide inserts provides a better surface finish at a same cutting speed. During experiment, PCBN tool experience, both adhesion and abrasion wear.

Sun et al. [2006] also analyze the tool life with a same cutting parameter and lubrication condition and observe that long tool life were achieved in MQL machining and also study the effect of cutting speed, radial depth and federate on the tool life Federate acts as a significant factor to increase tool life. It was concluded that as the cutting speed increases, tool life decreases, but in MQL, tool life was increasing as the cutting speed increases. Normally the radial depth of cut was increased tool life in all coolant conditions, but MQL condition provides better results over the other coolant method.

Toh [2006] performed the experiment to examine the consequence of different cutter path orientation on Hardened AISI H13 material by ball nose end mills under the dry state during high speed milling at a maximum preference angle of 75°. It was concluded that tool life was maximum at downward tool track orientation as compared of upward track generation. In upward tool path orientation, less tool life was achieved, which shows that it increases the tool wear and reduces surface roughness.

Liao and Lin [2007] investigated the performance of PVD 1025 indexable carbide inserts on the mold steel workpiece of 41 Hrc during dry and MQL cutting condition. It concluded that MQL condition increase tool life in all cutting conditions. If cutting speed was equal than the optimal value of the cutting speed, then constant oxide layer was formed which work as diffusion barrier and helps to increase the tool life. If the cutting speed was less than optimal value of the cutting speed, then less oxide layer was formed which increase the tool life accordingly less. If the cutting speed is higher than the optimal value, then there was no protective layer formed, which results thermal cracks, fluctuation of the temperature. No doubt MQL machining provides good result over the dry machining, but it is not preferred for extreme high speed machining.

Yang et al. [2007] performed the experiment on high purity graphite product and carbide tool whose diameter was 10 mm under dry machining during grooving operation produced in end milling and measured the surface roughness of inside groove i.e. Bottom plane and bottom width as well as analyzed the optimal cutting parameter. It was concluded that feed rate plays an important role to provide a good surface finish as well as groove difference. As the feed rate reduces, flank wear increases on the tool but feed rate also help to increase the surface quality as well as reduce groove difference.

Braghini et al. [2009] performed end milling operation on stainless steel under different cooling and lubrication conditions such as dry, oil with compressed air, flood oil, and low flow of oil. It concluded that low flow oil provides better tool life than flood cutting as well as dry cutting. But dry cutting gives better tool life than flood cutting. During experiment, it was noticed that MQL provides better results than other lubrication and also reduce the tool wear and increase the tool life.

Siller et al. [2009] investigated the effect of particular carbide PVD AlCrN coating tool on hardened steel in the face milling operation and measure the surface roughness, tool wear and flatness of the surface to analyze the best operating conditions. It concluded that the minimum value of the surface roughness was obtained from the experiment with a satisfactory tool life.

Liew, W.Y.H. [2010] performed the experiment to calculate the performance of uncoated carbide with coated carbide such as TiAlN/AlCrN coating, nanomultilayer coating and TiAlN single layer coating on a workpiece of 40 HRC and 55 HRC during flood and mist lubrication under low speed milling to know the effect of hardness over the tool wear. During experiment, it was noticed that flank wear increases as the hardness of the workpiece increases. TiAlN/AlCrN coating provides higher wear resistance than TiAlN coated as well as uncoated tool, whereas Nano multilayer coating offers better surface finish result as well as reduce tool wear and concluded that coating provide a shield of the tool against the crack, fracture and catastrophic failure as well as increase the ability to cut workpiece at high length. Mist lubrication offers good results over the flood lubrication. It reduces the development of catastrophic failure and abrasion wear during cutting operation and avoid the formation of adhesion wear.

Zhang and Li. [2010] proposed the relationship among tool wear, surface topography and surface roughness as well as find the optimal value of the flank wear which affect the tool life and surface roughness during finish milling process. It performed the experiment by layer by layer cutting of the workpiece in the interval of 2, 4, 6, 8, 10 min and analysis the tool wear and surface roughness after cutting each layer. It analysis with the result that first two layers have less tool wear and surface roughness, but last two layers have start rapid tool wear and surface roughness. They concluded that surface roughness increase with the increase of tool wear. Tool wear and flank wear increase as the cutting time increases.

Ozcelik et al. [2011] measure the surface roughness of the workpiece of the same experiment to evaluate the performance of the inserts on AISI workpiece under dry and wet machining during end milling operation. In this experiment, they measure the surface roughness under these operating conditions and compare the results. It concluded that in some cases dry milling gave lower surface roughness as compared to the presence of cutting fluid in milling machining.

Yuan et al. [2011] also investigated the tool wear at same cutting and observed that in 0 ℃ cooling, large flank wear and notch weir generated during dry, wet, MQL (without cooling air) and MQL (with cooling air) condition, but in MQL (with cooling air), flank wear and notch wear both decreases at -15˚C, -30˚C, -45˚C cooling.

Hao et al. [2012] investigated the same experiment and also analyze the tool wear under same cutting condition. In this experiment they vary the cutting speed with fixed feed rate as well as depth of cut and measure the tool wear, wear mechanism. It was concluded that a workpiece material adhered to tool face to form adhesion layer. The unstable adhesion layer peeled off from tool substrates and for a pair of tool-workpiece in cutting process, there was an optimal temperature that makes tool-workpiece had an optimal strength ratio as well as minimal tool wear.

Premnath et al. [2012] performed the experiments on tungsten carbide and hybrid composite during dry machining under milling condition. It studied the effect of weight of the weight fraction of Al2O3 and machining parameters such as cutting speed, depth of cut, federate on the surface roughness as well as cutting force. It concluded that less cutting force and surface roughness were achieved during low federate and high spindle speed, but some micro-scratches as well as feed marks were shown at higher feed rate machining. Flank wear was noticed due to high pressure generated at the tool-workpiece interface.

Zhang et al. [2012] investigated the off line prediction of the tool wear by mapping the aluminum alloy material which was low influence of the wear into the workpiece (stainless steel). In this study the tool wear was measured in three stages at initial, steady stage and failure stage. The experiments were conducted in cemented carbide ball end cutter of two different diameters such as 16 mm and 12 mm and performing nine experiments on each of the two different diameter of the tool to analyze the tool wear at different stages. A new tool was used to mill on a mapping plate and that first hole was taken as reference. Now the cutter became worn was used to mill another hole on the mapping plate. The feed distance between the two holes was same. Cleaning the metal piece and compares the tool wear from the worn cutter hole with the reference hole. CMM was used to measure the tool wear. These studies was help in continuous production process and provide a new approach for estimating the tool wear such as flank wear, radial wear and crater wear. It concluded that this study was useful and practical to measure or analyzes the tool wear.

Fan et al. [2013] performed the experiment to measure the effect of tool material, tool shape, cutting parameters on the surface quality and analyzed the tool wear, machined surface morphology, as well as the effect of built-up-edge, and chip side flow on the surface quality using PVD-TiAlN coated tools on Inconnel 718 in dry machining. It performed the experiment in which cutting speed was varied such as 25, 35, and 45 m/min at fixed depth of cut as well as feed rate (ap =1 mm, f=0.12 mm/rev). The result shows that when cutting speed was 25 m /min, then lots of materials adhering to the machine surface as well as formation of built up edge. When cutting speed was 45 m/min, there was plastic deformation, heavy tool wear and burr formation in the machined surface which led to surface breakage, but when cutting speed was 35 m/min, smooth machine surface was obtained. There were less tool wear to occur other than the remaining two cutting speeds.

Niu et al. [2013] evaluated the performance PVD-(TiN+TiAlN) and CVD (TiN+Al_2O_3+TiCN) coated tool inserts on two different titanium alloys such as TC11 and TC17 under face milling and measured the effect of the machining parameters on cutting forces, surface roughness and chips morphology as well wear mechanism. It was concluded that TC17 alloy was more difficult-to-cut material than TC11 alloy. In PVD coated inserts, crater wear and chipping were the dominant failure where as In CVD coated insert, flank wear and breakage.

Pathak et al. [2013] also investigated the tool wear under same cutting conditions to evaluate the effect of these parameters on the surface roughness by using a surface roughness tester. It concluded that as the cutting speed increases It concluded that as the cutting speed increases, then it reduces cutting force. Mostly cutting forces increases with feed rate and depth of cut. Chip thickness also depends on the increase of cutting force. During experiment, it was noticed the effect of cutting force by the depth of cut as compare to the feed rate and cutting speed.

Wang et al. [2014] evaluated the wear performance of uncoated tool inserts and PVD coated tool inserts in face milling on Inconel 182 during up or down milling under different lubrication conditions such as dry cutting and MQL with different nozzle positioned such as tool cut into work piece as well as tool cut out of work piece. To investigate the flank wear rate, tool failure modes and wear mechanisms by evaluating the volume of removal, metal during up and down milling of uncoated tool inserts and PVD coated tool inserts. It concludes that PVD coated tool inserts have a longer tool life compared to uncoated ones in all lubrication conditions. In up milling, catastrophic breakage, notching and coating cracking are the failure modes in dry and MQL cutting condition. It was noticed that MQL produce a longer tool life of PVD coated tool inserts, but the lubrication efficiency of MQL nozzle whose positioned was at the tail cut out of work piece is better than that at tool into of work piece. However, in down milling, MQL can also effectively reduced tool wear of PVD coated tool inserts.

Zhu et al. [2014] performed a simulated study by facilitating heat-pipe in the end milling operation to measure the tool wear, tool life and cutting temperature and compared the results with dry and flood cooling milling operation. In this study it model two end mills with the help of solid works with and without planting heat pipe on it and analyzed by FEM analysis. It takes six tools of hard alloy end mill with three cutting edges and workpiece was an AISI 1040 steel block. Each two tools were used in the three different cooling conditions and it was analyzed that heat pipe embedded end mill gives better result as compared to other two cooling operations. Heat embedded pipe was most suitable for the end milling operation. It increases the cutting temperature on the tooltip, reducing tool wear and also helps to increase the tool life by the maximum reduction of the thermal stress, which was induced in the internal as well as the external tip of the tool.

2.3 Scopes and Objectives

Literature shows that an extensive amount of work had been done by the previous investigators in modeling, simulation and parametric optimization of the product in end milling operation. Issues related to tool life, tool wear, cutting forces, surface finish, tool failure modes, white layer formation, formation of cracks, edge chipping, cutting temperature, online monitoring tool wear, surface topography, surface texture, vibration have been addressed. [Reddy and Rao, 2007; Zhang et al., 2007; Cao et al., 2013; Pathak et al., 2013; Tian et al., 2013] measures the cutting forces which are generated with the tool at the time of machining. Few literature surveys are based on the monitoring tool wear, tool mode and tool life [Braghini et al., 2001; Toh, 2004; Jawaid et al., 2008; Siller et al., 2008; Braghini et al., 2009; Zhang and Li, 2010; Zhang et al., 2011; Wang et al., 2014; Zhu et al., 2014]. Most of the researcher also works on the surface roughness and surface topography [Ekinovi et al., 2007; Reddy and Rao, 2007; Bruni et al., 2008; Siller et al., 2009; Tosun and Huseyinoglu, 2010; Zhang and Li, 2010; Ding et al., 2011; Zhang et al., 2012; Fan et al., 2013; Pathak et al., 2013; Cai et al., 2014]. Toh, 2007 measures the surface topography, surface texture and surface roughness, cutting forces and vibration by using different cutter path strategies such as offset, raster, and single-direction raster strategies. Yang et al., 2007 use the orthogonal array for grey relation theory to measure the surface roughness of the inside grooves at bottom plane as well as bottom width.

From beginning to end there are several literature surveys which have considered four main parameters for their experiments such as Speed, Feed axial depth of cut and Radial depth of cut. Based on these literature surveys and knowledge of the experiments the following three factors were considered in the experimentation process.

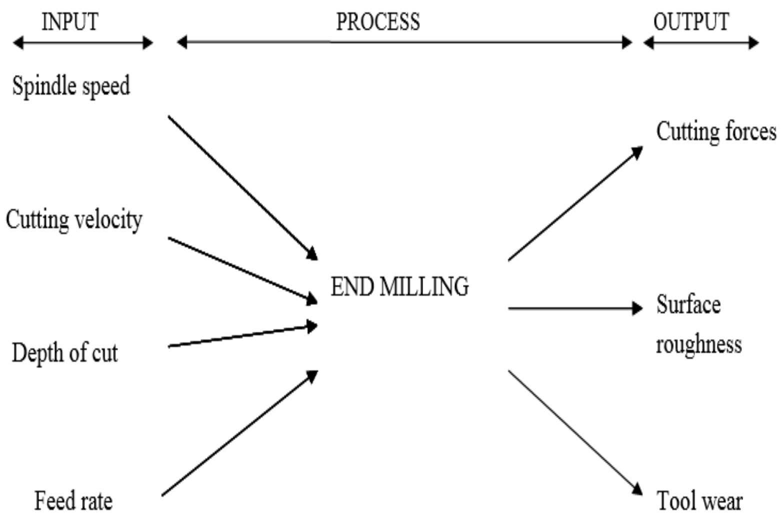


Figure 2.1 Schematic diagram to represent input and output variable considered during end milling

The experiment will be performed by varying there factors. The objective of the thesis work will be achieved by following these steps.

- Experimental investigation to evaluate the performance of different PVD coated inserts such as (TiCN+TiN, TiAlN+TiN) during end milling of hardened die steel (EN–31 material) of varying cutting speed, depth of cut and feed rate.
- Comparison of performance of these inserts between dry and MQL machining condition.
- Comparison of cutting forces, surface roughness and tool wear at a fixed feed rate, depth of cut under different cutting speed.
- Experimental investigation to evaluate the performance of different CVD coated inserts (TiCN+Al_2O_3+TiN. 0315, TiCN+Al_2O_3 +TiN) during end milling of hardened die steel (EN–31 material) at different cutting speed under fixed depth of cut and feed rate.
- Comparison of performance of these inserts between dry and MQL.
- Comparison of cutting forces, surface roughness and tool wear under varying cutting speed at fixed feed rate and depth of cut.
- Compare the performance of CVD insert and PVD inserts.

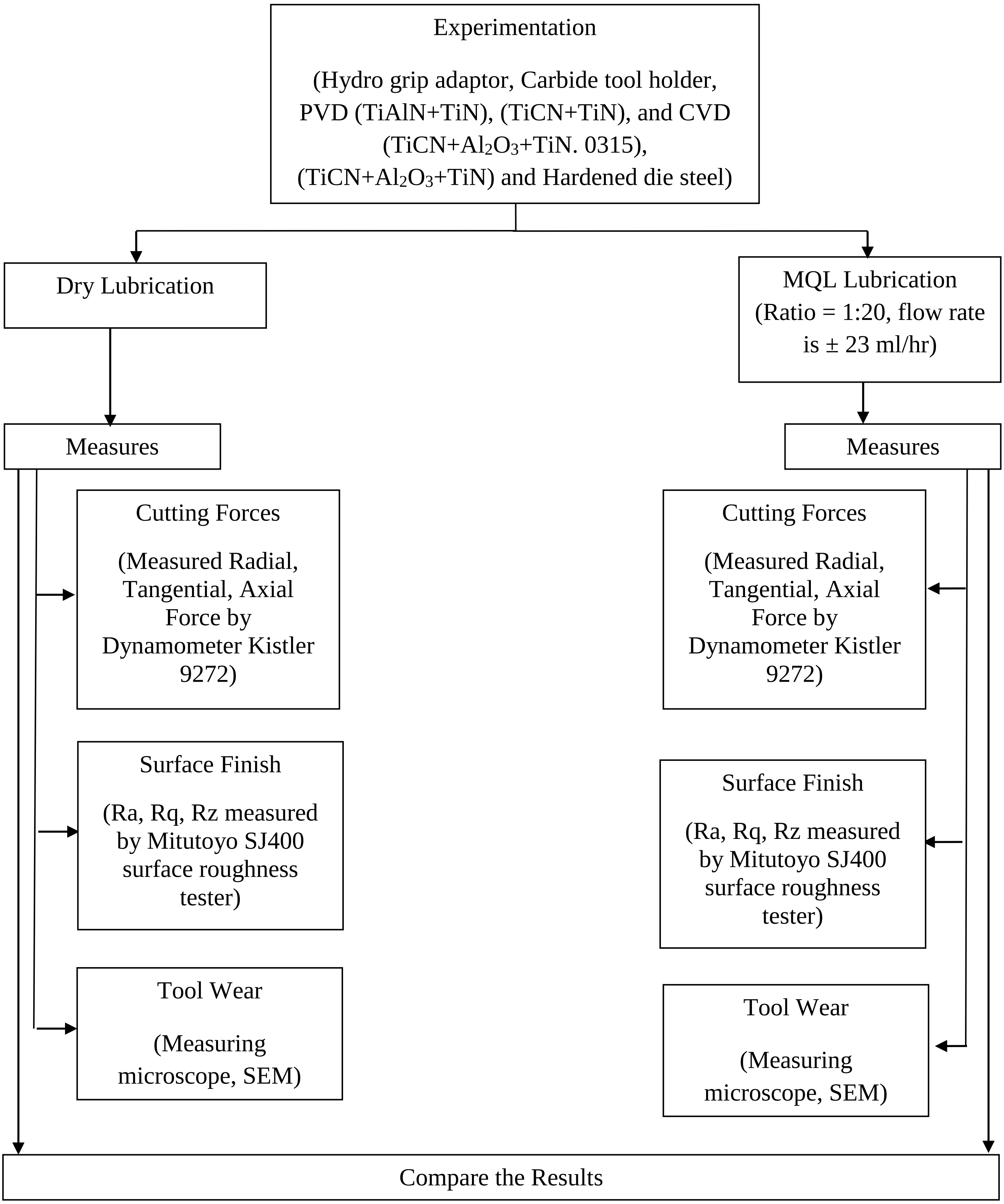


Figure 2.2: Flowchart of overview for thesis

CHAPTER 3

MATERIALS AND METHODOLOGY

3.1 Introduction

This chapter gives a sketch about the tool geometry, workpiece, milling machine, MQL setup, machining and measurement (cutting force, surface finish and tool wear) are used in this experiment. Finally a brief introduction to the experimental methodology is discussed.

3.2 CNC Vertical Milling Machine

A CNC 3 axis machine is used for cutting the workpiece. Machine maximum max power is 3.7 KW, its spindle nose taper and tool holder taper is BT 40 and max spindle speed is 60-6000 rpm. The transverse movement of the table (x- axis), saddle (y-axis) and spindle (z-axis) is 800, 350 and 380. CNC machine BT-40 works safely up to the feed rates 5000 mm/min. Rapid transverse movement in X, Y, Z direction is 15/15/10 and the ball screw diameter and pitch is 32*10 mm. Machine table specification, clamping area mm×mm is 1060×315, number of T-Slot is 3. The center distance/slot wide mm/mm is 14/100. Load carrying capacity of the table is 300 kg and distance from the table top to spindle face is 75 – 455 mm, distance from spindle center to column face is 480 mm and the distance from floor to table top is 10 mm.

3.3 Workpiece Material

EN-31 hardened die steel workpiece is used in this experiment with the chemical composition of the workpiece material is shown in Table 3.1 and whose length is 110 mm, breadth is 65 and height is 18 as shown in Fig. 3.1. EN-31 material is also called low alloy steel and it is used frequently due to its less cost as well as its providing better material properties. It encloses nearly 0.05–0.320% carbon, which makes it malleable and ductile. It has comparably low tensile strength. The density of mild steel is approximately 7.85 g/cm^3 and the Young's modulus is 210 GPa.

Table 3.1: Chemical Composition of the Workpiece Material

Fe%	C%	Si%	Mn%	P%	S%	Cr%	Mo%	Ni%	Al%
97	0.862	0.192	0.461	0.0725	0.0649	1.17	0.023	0.0123	0.02
Co%	Cu%	Nb%	Ti%	V%	N%	Pb%	Sn%	B%	Ca%
0.0076	0.0391	0.0023	<0.0020	<0.0020	<0.0150	<0.025	0.0161	<0.001	.0002

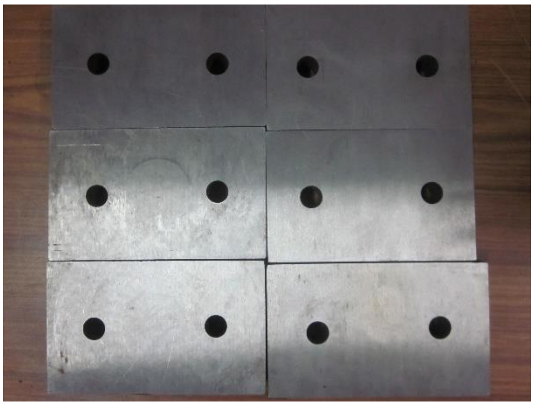


Figure 3.1: EN-31 workpiece

3.4 Tool Materials and Tool Geometry

The carbide tool holder is R390-020A20-11L provided by Sandvik coromant and has a diameter of 20 mm. It is coupled with a Hydro grip adapter BT40-SHYD20-095M which is provided by the Birla Kennametal as shown in Fig. 3.2, is used in the CNC milling machine and then run out of the hydro grip adaptor is 0-2 microns. PVD (TiAlN+TiN), (TiCN+TiN), and CVD (TiCN+Al_2O_3+TiN. 0315), (TiCN+Al_2O_3+TiN) are used for this experiment, the thickness is shown in Table 3.2. The tool has the capacity to be loaded with single rows of inserts with two inserts in a row and move in x, y, z direction during cutting as shown in Fig. 3.3. The insert is a parallelogram in shape. The tool has been specifically designed to profile and finish milling applications in the aerospace industry. The machine has a 2 jaw chuck to hold the work piece. The tool holder is held in the 2 jaw chuck. Hydro grip adaptor and carbide tool of diameter 20 mm are used to perform the milling operation. The carbide tool first inserts in the hydro grip tool holder. Then this hydro grip tool holder is held in the 2 jaw chuck by clicking the tool clamping button. The CNC program can be fed into the machine by using or applying G and M codes and the program is run. Figure 3.4 shows an image of the actual insert used in the experiments. The flank face of the tool is shown in Fig. 3.5

Table 3.2: Inserts coating thickness

Coating thickness	PVD 1025	PVD 1030	CVD 4240	CVD 4230
	3 µm	4 µm	9 µm	4 µm

(a)

(b)

(c)

Figure 3.2: (a) Hydro grip holder, (b) carbide tool (c) Assembly of holder and tool

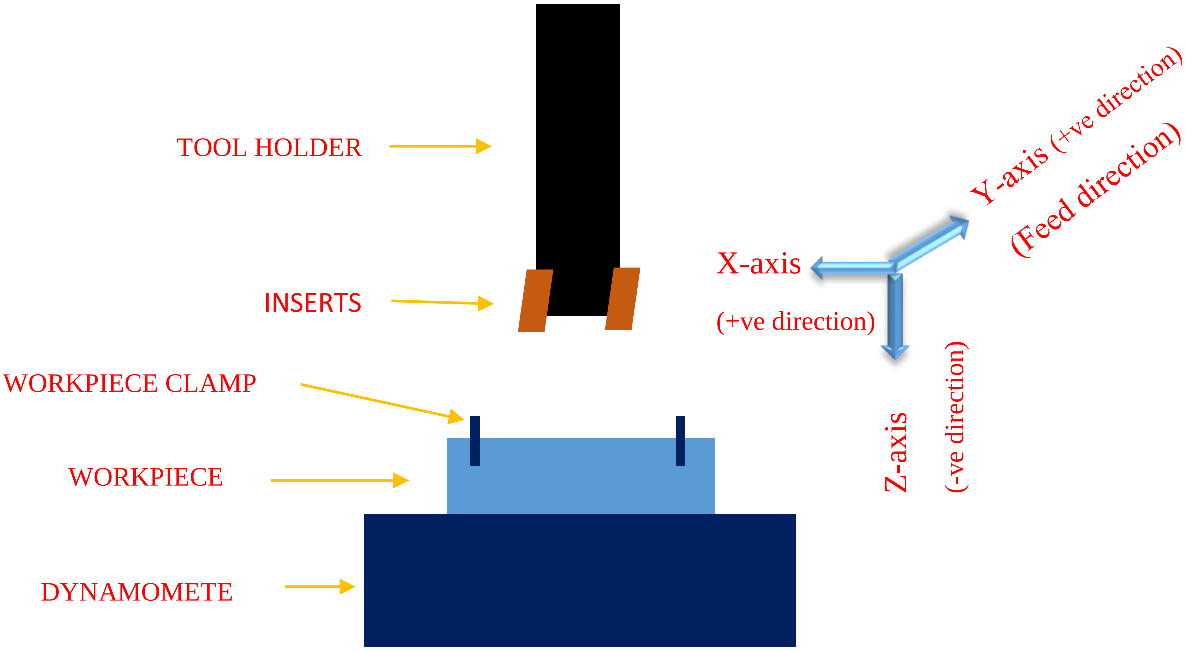
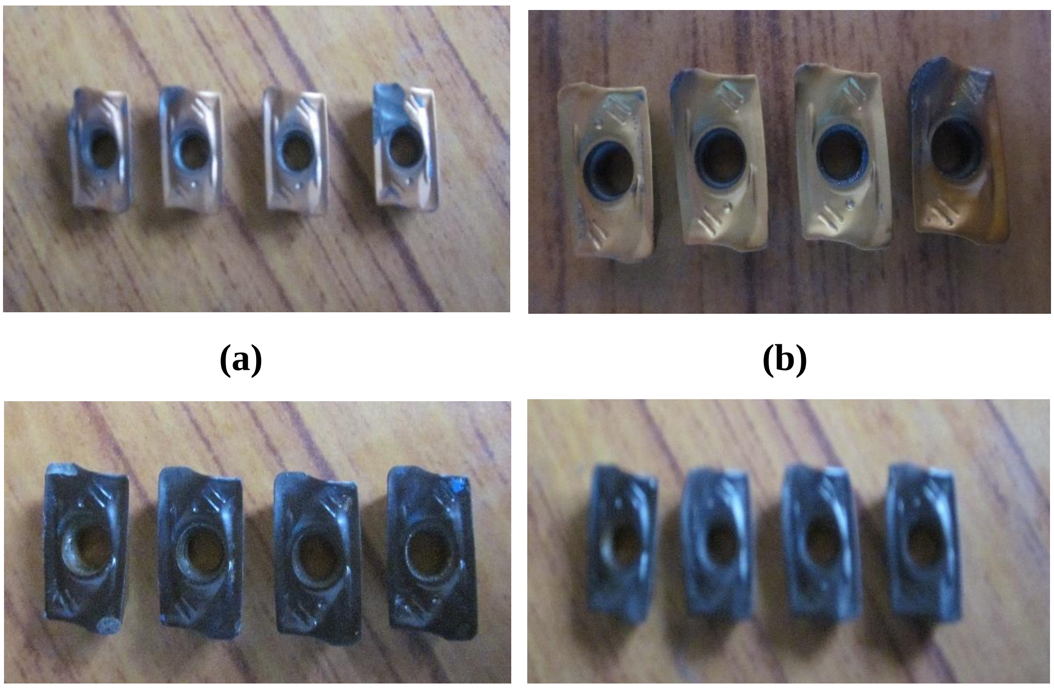


Figure 3.3: Movement of tool in x, y, z direction



(a) **(b)**

(c) **(d)**

Figure 3.4: Carbide Inserts (a) PVD tool A (b) PVD tool B (c) CVD tool A (d) CVD tool B

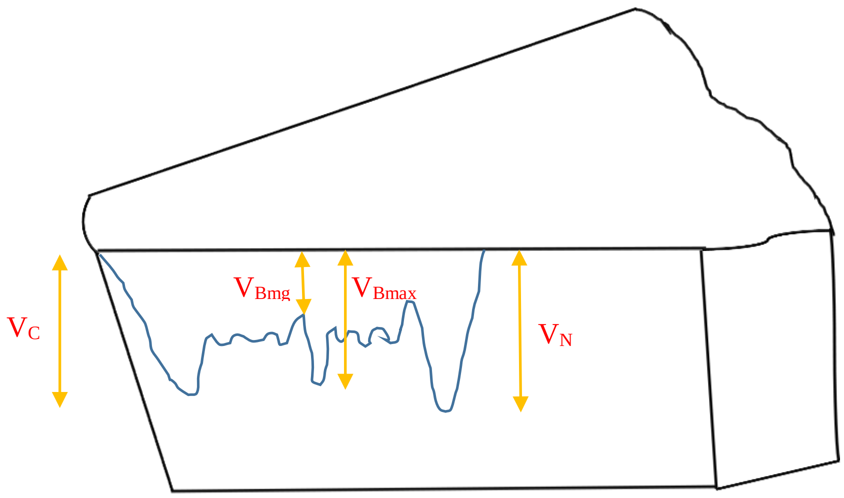


Figure 3.5: Schematic representation of flank wear on tool flank surface

Experimental Design

The experiment is conducted in a two condition of machining i.e. Dry and MQL in two different stages. On the first stage, the experiment is performed at a constant depth of cut of 3 mm, feed rate of 12 mm/min and cutting speeds 200 m/min to measure the cutting forces, surface roughness and tool wear of different carbide tool. The cutting experiment is stopped after machining 13.5 min or when a catastrophic failure occurs on tool inserts. In the second stage, the experiment is performed at fixed depth of cut of 1 mm, feed rate of 12 mm/min under varying cutting speed of different carbide tools to measure the cutting force, surface roughness and tool wear. The cutting experiment is stopped after 22.5 min or when catastrophic failure as well as a tool failure occurs at the tool tip.

3.5 Fabricated MQL Setup

Step 1

In this MQL setup, the first step is to join the three with T valve which has one inlet and two outlets. Inlet port is connected with the main supply of the pressure, so this main supply of the compressor is divided into two equal parts. One outlet is connected to the machine for starting the machine. The compressor is also used to change the tool. A second outlet is used for installing up the MQL setup for machining as shown in Fig. 3.6.

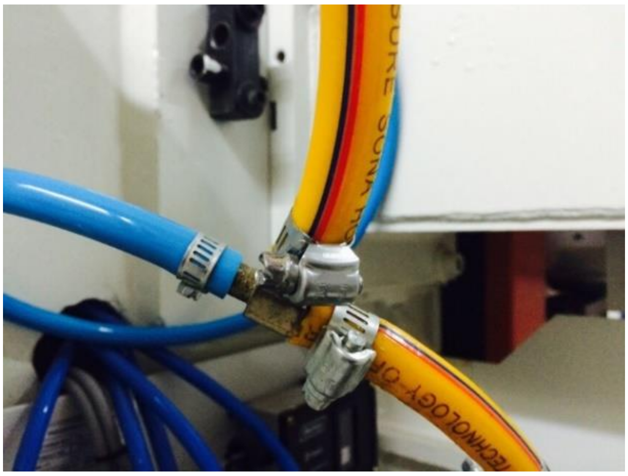


Figure 3.6: Branching of compress air

Step 2

Connect on / off valve which helps to off the compressor air when it is not required or it also help to adjust the pressure according to the experiment need. Clamps are used for proper fitting of the tube into the valve as shown in Fig. 3.7.

Figure 3.7: On/Off valve nozzle

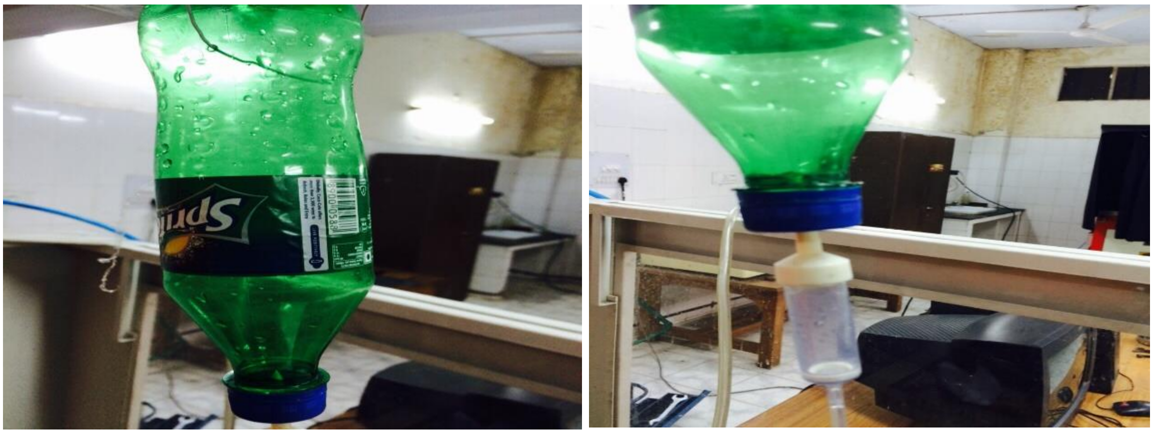
Step 3

A tapered type tube is connected with the pipe to minimize the pressure drop and increase the flow of compressed air. There is a needle connected to the tapered tube. This needle is used as an inlet port for the water. The needle is connected in this way to minimize the back pressure of the water as shown in Fig. 3.8.

Figure 3.8: Taper tube

Step 4

Coolant is stored in the bottle and there is a small hole in the cap of the bottle as shown in Fig. 3.9 (a). A coolant dropper is fitted in the coolant storage bottle as shown in Fig. 3.9 (b).



(a) (b)

Figure 3.9: (a) Coolant storage bottle (b) Coolant dropper is fitted in the coolant Storage bottle

Step 5

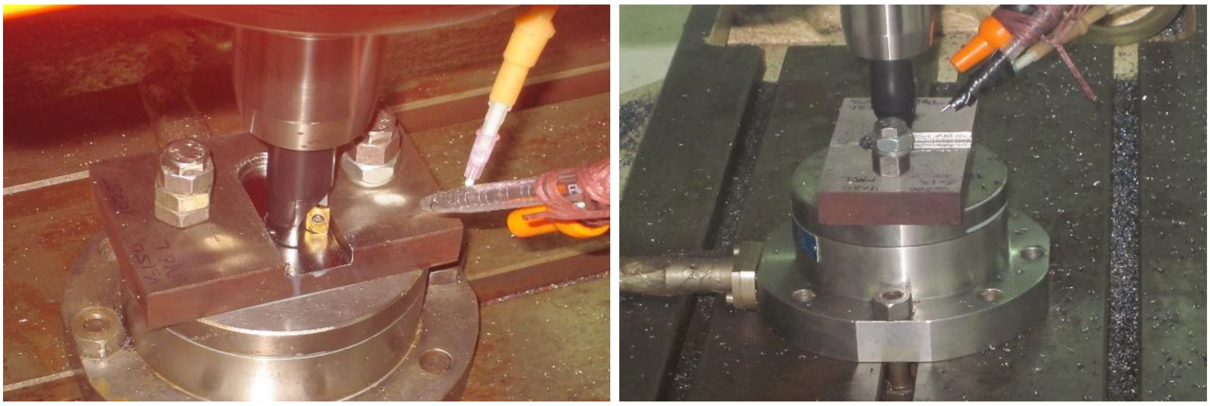
The coolant controller valve is set by which very small amount of water is released from the coolant container as shown in Fig. 3.10 (a). This outlet port is connected to the needle, which fits into the tapered nozzle, so that coolant droplet is released from the coolant storage bottle and it will easily break into the smallest particle to make a mist as shown in Fig. 3.10 (b).

(a) (b)

Figure 3.10: (a) Coolant controller (b) Coolant outlet pipe connected to Tapered nozzle

Step 6

Now this tapered nozzle is tied with the wet lubrication for giving a support and for the proper supply the coolant into the workpiece as shown in Fig. 3.11 (a). Dynamometer is used measure the cutting forces which are coming in MQL lubrication as shown in Fig. 3.11 (b).



(a) (b)

Figure 3.11: (a) MQL setup nozzle tie with wet lubrication (b) Dynamometer

In the MQL, cutting fluid was used at a ratio 1:20 in which 1 ml cutting fluid was mixed with 20 ml water for machining. The cutting fluid has been supplied to the tool–work piece surface at a flow rate of 20-23 ml/hr and the pressure of 6-7 bar has been supplied by the compressor air pipe. A schematic MQL diagram as shown in Fig. 3.12. Figure 3.13 represents the systematic diagram of MQL setup.

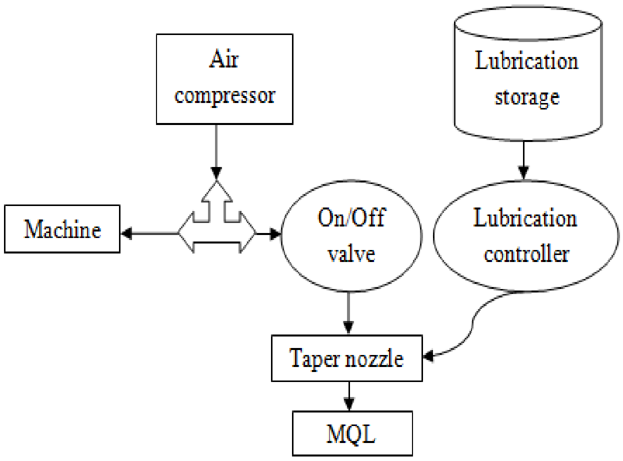


Figure 3.12: Flow chart of MQL setup

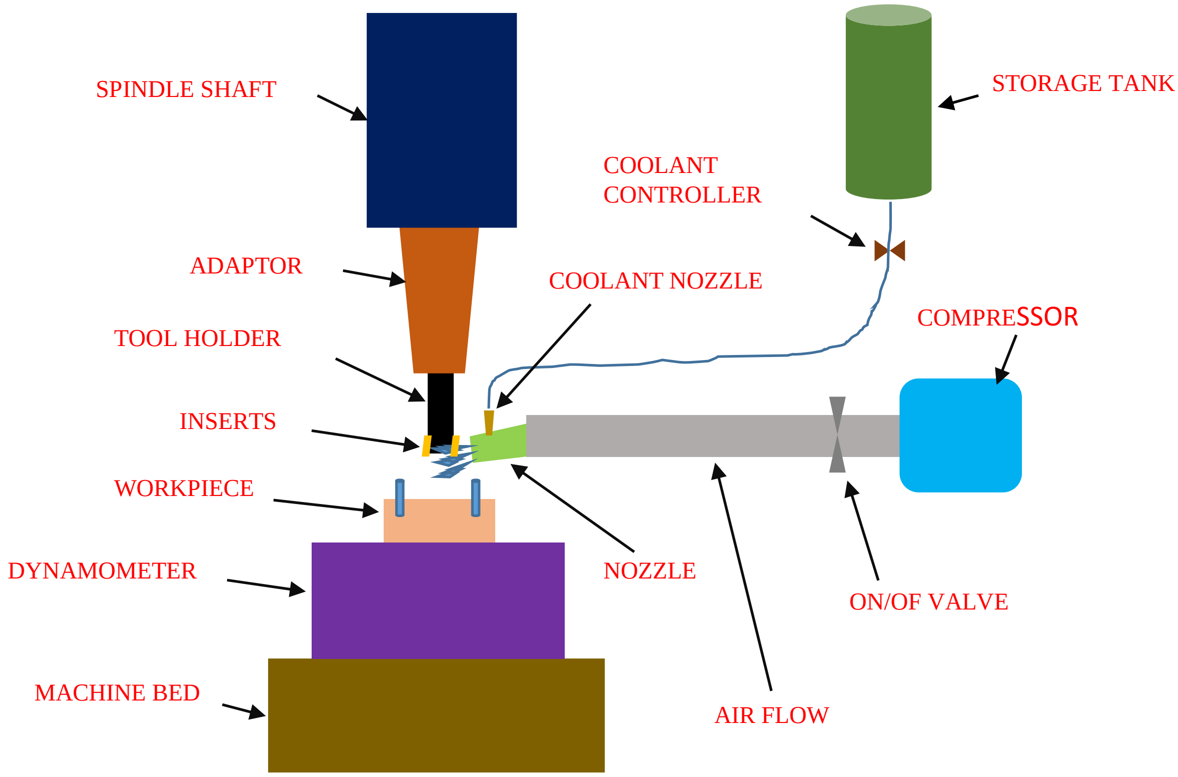


Figure 3.13: Schematic diagram of MQL setup

3.6 Measurements

3.6.1 Cutting Forces

Kistler Dynamometer 9272 is used to measure the cutting forces in dry lubrication as well as MQL (minimum quantity lubrication) machining. Workpiece mounted on the dynamometer to measure the cutting force. This dynamometer was connected to the desktop and save the data on that desktop as shown in Fig. 3.14 (c). A dynamometer is used to measure the cutting forces in all three axes (Fx, Fy and Fz) and torque, which act on the tool while machining as shown in Fig. 3.14. A dynamometer is placed on the table in which workpiece is clamped to measure the forces and power. Two operations are used to measure the cutting forces. The first operation is performed on the end milling by using dry lubrication and measures the cutting forces by the dynamometer. The second operation is done with MQL lubrication and measures the cutting forces. The surface of the workpiece should be clean after performing the end milling operation.

(a) (b) (c)

Figure 3.14: (a) Dynamometer setup (b) setup of the dynamometer (computer, amplifier, CPU, mouse, keyboard

3.6.2 Surface Roughness

The Mithutoyo surface roughness tester was used to measure the surface finish of the workpiece as shown in Fig. 3.15. Before start measuring the surface roughness machine should be calibrated. Surface roughness are evaluated by machining of the EN-31 material with a different coated carbide inserts under different machining condition such as dry and MQL machining.

Figure 3.15: Surface roughness tester

3.6.3 Tool Wear

A measuring microscope is used to measure the tool wear of the tool as shown in Fig. 3.16. The movement of measuring bed in x–direction is 70 mm and movement of measuring bed in y–direction is 50 mm. In tool wear, mainly two types of wear occur i.e. Crater wear and flank wear. Crater wear mainly occurs on the front face of the tool due to the flow of chips and formation of built-up edge, whereas flank wear is occurring on the flank face due to the small clearance angle as well as friction force. Tool wear measured after every cut of 4.5 min to evaluate the progress of the wear.

Figure 3.16: Measuring microscope

Table 3.3: Material used for experiments

Machine	CNC vertical milling machine
Workpiece	EN-31
Dimension	109×65×18
Tool insert	PVD(TiCN+TiN), PVD(TiAlN+TiN) and CVD (TiCN+Al_2O_3+TiN. 0315), CVD (TiCN+Al_2O_3+TiN)
Tool holder	R390-020A20-11L
Tool holder specification	20 mm diameter
Tool adaptor	BT40-SHYB20-095M
Environment	Dry and MQL machining
Measure	Cutting Force, Surface Roughness and Tool wear

CHAPTER 4

RESULT AND DISSCUSSION

4.1 Introduction

This chapter discussed the experimental analysis, which was performed during the experiment under different machining condition such as dry machining and MQL condition. The experiment was performed on different PVD and CVD inserts at different cutting conditions to measure the effect of varying cutting speed and depth of cut on the cutting force, surface roughness and tool wear. In this study, the experiment was performed in two stages. On the first stage, the experiment was performed under fixed feed rate and depth of cut at varying cutting speed to measure the effect cutting speed on cutting force, surface roughness and tool wear, whereas in the second stage, the experiment was performed under fixed federate, depth of cut and cutting speed to measure the performance of insert at high depth of cut. The purpose of this study to know or measure how efficiently cutting is done on the MQL condition under varying speed and what is the main reason which affects the cutting forces, surface roughness and tool wear during machining.

4.2 Measurement of cutting forces under Dry and MQL

In the material removal process, plastic deformation mainly occurs in the primary shear zone as well as friction between chip and tool interface due to the contact length of the chip to the tool. This contact of chips have two regions such slip region and stick region, which increase the high amount of heat between the tool and chip. There are many reasons to know about the cutting forces such as it helps in the design of the cutting tool, fixtures to hold the workpiece and cutting tool, avoid the distortion of the workpiece as well as help in the calculation of the machine tool power. In this experiment, it is noticed that cutting forces are less generates in MQL condition as compared to the dry machining because in MQL machining, cutting fluid are direct injected on the interface of the cutting tool and the workpiece as given in Table 4.1 (Cutting Force of different CVD and PVD inserts under different cutting condition at fixed feed rate = 12mm/min, depth of cut = 1mm and varying cutting speed). This method proves more effective than dry machining as MQL easily delivers the cutting fluid to the cutting zone area and decrease the radial forces which generates during machining whereas in dry machining, the cutting forces increases during machining. Cutting force measures three forces during cutting such as (radial, axial and tangential force). These three forces are shown in Fig. 4.1 but among all these three cutting forces, the major effect was shown in radial force which act in the feed direction, so further discussion has been done on the radial force and rest two forces are shown in appendix 1. Maximum radial force was measured at 4.5 min of cutting.

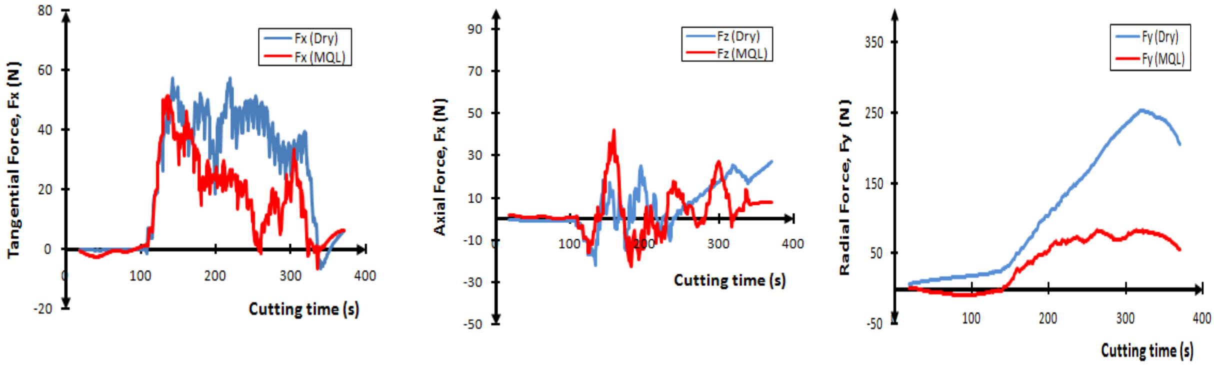


Figure 4.1: Cutting forces raised during cutting operation (tangential, axial and radial force)

4.2.1 PVD 1025 inserts

PVD insert has a TiCN+TiN coating with two cutting edge and its recommended cutting speed is 235–250 m/min. Nose radius of the insert is 0.8 mm. This coating is suitable for steel as well as stainless steel materials. Mainly this insert is used for the light cut. In this investigation, the experiment was performed on PVD 1025 inserts to measure the cutting forces at constant feed rate of 12 mm/min, depth of cut 1 mm, and cutting speed of 150, 175, 200 m/min. The experiment was performed in five repetition cut. Cutting force was measured in intervals of every 4.5 min till 22.5 min of machining, after every cut of 55 mm measured the individual performance of PVD 1025 coated inert. All the reading of the cutting force were collected during the experiment and compared with the performance of the insert on the different machining (Dry and MQL) condition.

Figure 4.2 (a) shows that cutting force increases with a cutting time, but after a certain time it decreases. MQL machining generates less cutting force during all cut in cutting operation, whereas dry machining generates high cutting force. According to the Fig. 4.2 (a), dry machining gradually increases the cutting force with cutting time and achieve higher cutting force at cutting time of 18 min as well as sudden drop of cutting force at 22.5 min of cutting time was seen, whereas in MQL machining, cutting force increases slowly and achieve higher cutting force at a 13.5 min of cutting time then it drop the cutting force and gradually decreases the cutting force with increase of cutting time up to 22.5 min of machining. MQL condition achieves less cutting force as compared to the dry condition in all cutting time.

Figure 4.2 (b) shows that cutting under dry condition provides higher cutting force at cutting speed 175 m/min. Cutting force rapidly increases at first cut of 4.5 min and then gradually increases, whereas In MQL condition, very less amount of cutting force, generate during cutting operation and there is no sudden increase or decrease in the cutting forces as the cutting time increases. Higher cutting forces increases in both cutting conditions as compared to the cutting speed of 150, 200 m/min.

Figure 4.2 (c) shows that cutting force increases with time in dry condition but after reaching its maximum cutting forces, it suddenly drop the cutting force with the increase of the cutting time. Whereas in MQL machining, the cutting force increases gradually with cutting time and after machining of 9 min cutting forces increases with cutting time. The result shows that in MQL condition, less cutting force is generated as compared with the dry condition. PVD tool B experience less cutting force at cutting 200 m/min cutting speed as compared to the cutting speed 175 m/min and 150 m/min but after the third cut, cutting force rapidly increase at cutting speed 200 m/min whereas at 150 and 175 m/min cutting forces remain less as compare to the 200m/min. PVD 1025 experience the less cutting force after three cuts of cutting speed of 150 m/min cutting speed. PVD 1025 gives good results at cutting speed of 150 m/min in both dry and MQL machining conditions. Hence, PVD 1025 insert is suitable for light cut.

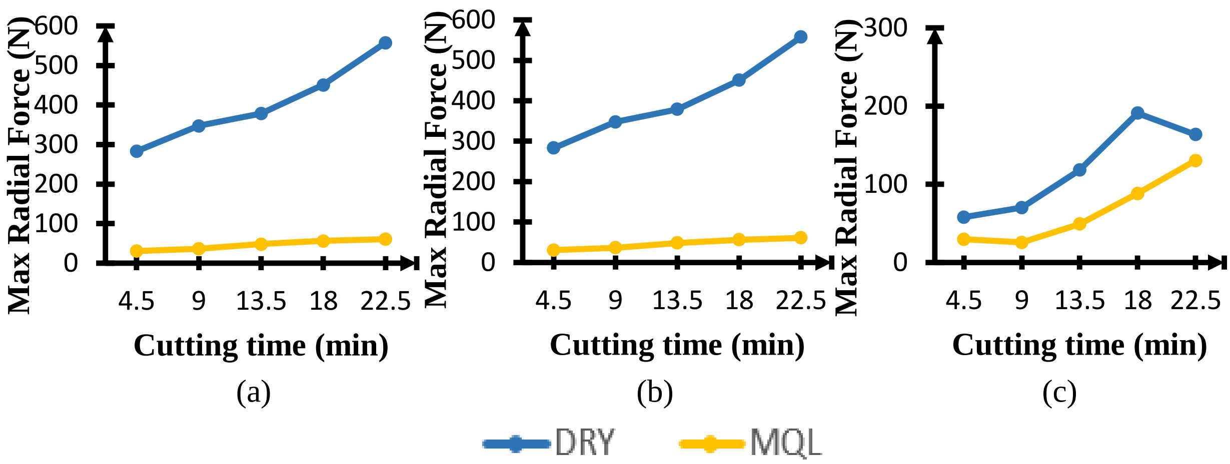


Figure 4.2: Cutting force result of the inserts after 22.5 min under fixed conditions (f=12 mm/min, doc= 1 mm) at a different cutting speed (a) at 150 m/min, (b) at 175 m/min, (c) at 200 m/min.

4.2.2 PVD 1030 inserts

PVD insert has a TiAlN+TiN coating with two cutting edge and its recommended cutting speed is 260–270 m/min. Nose radius of the insert is 0.8 mm. This coating is suitable for steel as well as stainless steel materials. This coating is harder as well as more stable with other coating and it has the ability to work under high temperature. In this investigation, the experiment is performed on PVD 1030 inserts to measure the cutting forces at constant feed rate of 12 mm/min, depth of cut of 1 mm, and cutting speed of 175, 200, 225 m/min. The experiment was performed in five repetition cut. Cutting force was measured in intervals of every 4.5 min till 22.5 min of machining, after every cut of 55 mm the individual performance of PVD 1030 coated inert was measured. All reading of the cutting force was collected during the experiment and compared for the performance of the insert on the different machining (Dry and MQL) condition.

Figure 4.3 (a) shows that after machining 13.5 min at cutting speed of 175 m/min, tool experience catastrophic failure in dry condition. Dry cutting generates higher cutting force at cutting speed ofs 175 m/min as compared to the cutting speed of 200, 225 m/min, whereas in MQL machining, cutting force rapidly increase after first cut of 4.5 min and then gradually increase the cutting force with respect cutting time. MQL machining increases the cutting ability of tool at higher cutting speed as well as help to reduce the cutting force which generate on the cutting zone during cutting operation.

Figure 4.3 (b) shows that in dry condition cutting force gradually increase up to the third cut of 13.5 min machining, but after 13.5 min machining, the cutting force rapidly increases at 18 min as well as sudden drop in 22.5 min whereas in MQL machining, the cutting force gradually with cutting time. MQL condition gives lower cutting force at all the machining time. Cutting force gradually increase with cutting time, but after 18 min of cutting, cutting force sudden drop with increase of cutting time, whereas In MQL condition, cutting force first increase with increase of time and then after 18 min of machining it sudden drop with the increase of machining time as shown in Fig 4.3 (c). MQL provides lower cutting force in all cutting time as compared to the dry condition. During the experiment, it observed that less cutting force is achieved at cutting speed Vc = 200 m/min in both dry and MQL conditions as compared to the other cutting speed. MQL provides less cutting force as compared to the dry condition.

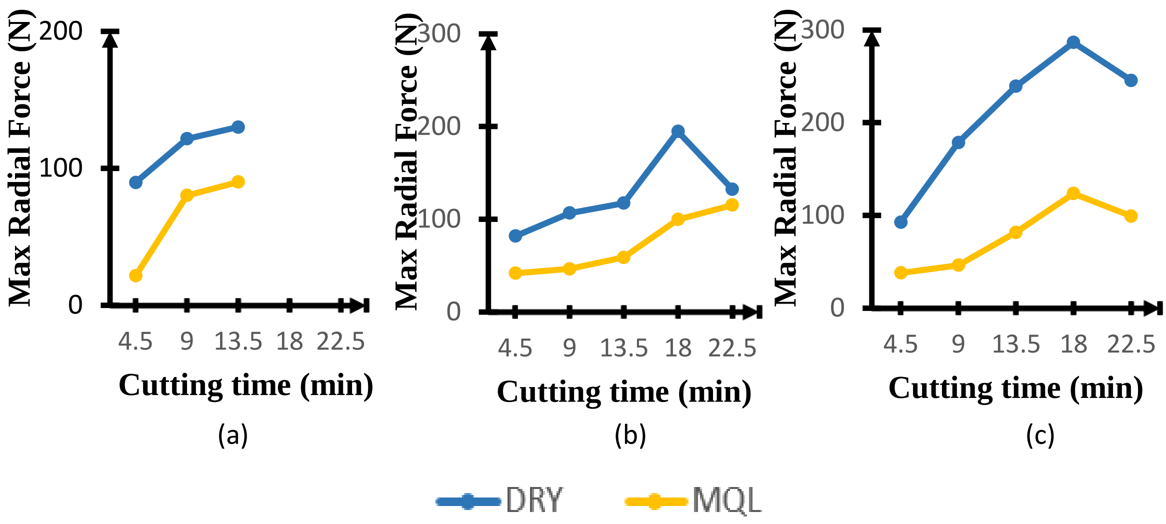


Figure 4.3: Cutting force result of the inserts after 22.5 min under fixed conditions (f=12 mm/min, doc= 1 mm) at a different cutting speed (a) at 175 m/min, (b) at 200 m/min, (c) at 225 m/min.

4.2.3 Comparison between PVD 1025 and PVD 1030 inserts

The experiment was performed in two different PVD inserts at different cutting speed. PVD 1025 performed the cutting operation at cutting speed of 150, 175, 200 m/min whereas as PVD 1030 cut the material at cutting speed of 175, 200, 225 m/min but the comparison is done between the cutting speed of two PVD insert at cutting speed of 175, 200 m/min. At cutting speed of 175 m/min, PVD 1030 provides better result in dry condition as well as experience the catastrophic failure after 13.5 min machining as shown in Fig 4.4 (a) whereas PVD 1025 provide good result in MQL at cutting speed of 175 m/min.

Figure 4.4 (b) shows that PVD 1025 provides good result in dry as well as MQL at cutting speed of 200 m/min as compared to the PVD 1030. This comparison shows that PVD 1025 achieved less cutting force during the experiment and it has the capability to work at high cutting speed.

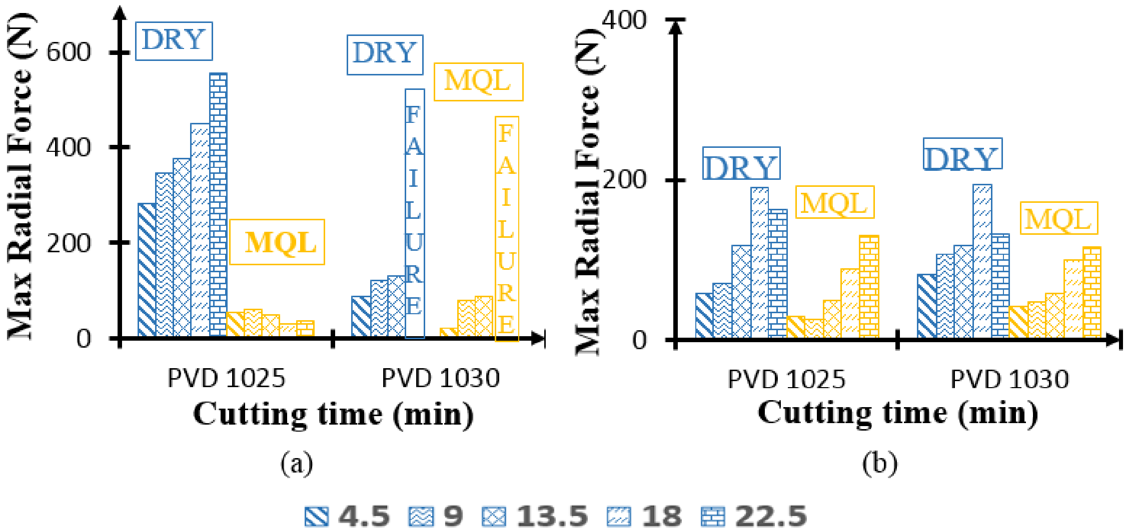


Figure 4.4: Maximum Radial cutting forces of PVD 1025 and PVD 1030 under the dry and MQL condition at fixed f = 12 mm/min, doc = 1 mm under variable cutting speed (a) Vc = 175 m/min (b) Vc = 200 m/min.

4.2.4 CVD 4240 inserts

CVD insert has a TiCN+Al_2O_3+TiN coating with two cutting edge and its recommended cutting speed is 260–270 m/min. Nose radius of the insert is 0.8 mm. In CVD 4240, there are three layer before substract. First layer of the coating in flank face provides wear detection, second layer help to minimize the chemical wear and third layer provide smoother machining. Substract of this insert will not crack easily because it is rich in cobalt with small sized grained. No material is stick during cutting operation on the rake face. Coating thickness of this insert is 9 µm. The experiment is performed on CVD 4240 inserts to measure the cutting forces at constant feed rate of 12mm/min, depth of cut of 1 mm, and cutting speed of 175, 200,225 m/min. The experiment was performed in five repetition cut. Cutting force was measured in intervals of every 4.5 min till 22.5 min of machining, after every cut of 55 mm it measures the individual performance of CVD 4240 coated inert. All reading of the cutting force was noted during the experiment and was compared for the performance of the insert on the different machining (Dry and MQL) condition. In CVD 4240 insert which is also called CVD tool A. In this inserts, cutting force slowly increases at 9 min of machining and after 9 min machining cutting force rapidly increase. Cutting force sudden drop after 13.5 min of cutting and gradually decrease up to 22.5 min, whereas in MQL condition, less cutting force generates as compare with the dry condition under all machining time. Cutting force slowly increase up to 13.5 min of cutting and then gradually decreases up to 22.5 min as shown in Fig 4.5 (a).

Figure 4.5 (b) shows that in dry condition, cutting force rapidly increase at cutting speed of 200 m/min during the second cut off 9 min machining after that cutting force gradually increases and sudden drop at 18 min machining. Cutting force increases after the fourth cut of 18 min. In MQL condition, the cutting force decreases gradually in the second cut after that it increases up to 18 min of cutting and then slightly decreases.

Figure 4.5 (c) shows that cutting force slowly increase with cutting time at a cutting speed of 225 m/min and then cutting force sudden drop with increase of cutting time at 18 min of machining. After 18 min cutting force again rapidly increase in dry condition, whereas in MQL condition, cutting force increase, but gradually decrease as the cutting time increases and again increase at 22.5 min of cutting. In dry conditions, cutting force abruptly changes to increase by machining time, but in MQL condition, cutting force gradually decrease with respect to cutting time.

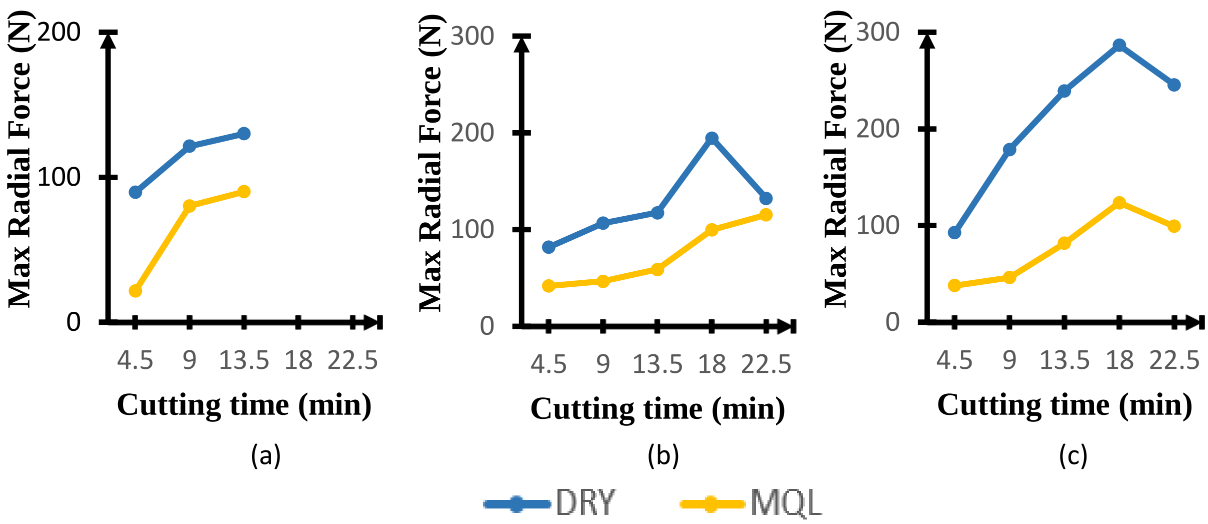


Figure 4.5: Cutting force result of the inserts after 22.5 min under fixed conditions (f=12 mm/min, doc= 1 mm) at a different cutting speed (a) at 175 m/min, (b) at 200 m/min, (c) at 225 m/min.

4.2.5 CVD 4230 inserts

CVD insert has a $TiCN+Al_2O_3+TiN$.0315 coating with two cutting edge and its recommended cutting speed is 310–315 m/min. Nose radius of the insert is 0.8 mm. In CVD 4230, there are also three layer before substract. In first layer of coating in flank face is facilitates for wear detection, second layer provides the good performance of enhanced aluminum oxide coating which act as a strong barrier against chemical wear and third layer of the insert is thin coating which provides smoother machining without flaking. The substract of the coating is strong. In this insert, low stress technology is used which strengthen the edge line, toughness and achieved better comb crack resistance and less built-up-edge. This insert is better for all CVD grade inserts. The coating thickness of this inserts is 4 µm. Cutting force is measured on CVD 4230 inserts at constant feed rate of 12mm/min, depth of cut of 1 mm, and cutting speed 200,225,250 m/min. The experiment is performed in five repetition cut. Tool wear is measured in intervals of every 4.5 min till 22.5 min of machining, after every cut of 55 mm measure the individual performance of CVD 4230 coated inert in different cutting speed. Collect the all reading of the tool wear and compare the performance of these coated inserts on the different machining (Dry and MQL) condition as shown in Fig. 4.6.

Figure 4.6 (a) shows that cutting force rapidly increase after cutting first cut of 4.5 min but after second cut of 9 min, cutting force gradually increase up to 22.5 min, whereas in MQL condition, the cutting force slowly increases at 13.5 min of machining and then decrease up to 22.5 min of cutting. MQL condition provides better results over the dry machining.

Figure 4.6 (b) shows that cutting force increases with cutting time, but after 13.5 min of cutting, cutting force suddenly dropped at 18 min and abruptly increases at 22.5 min of cutting, whereas in MQL machining, cutting force gradually increase with machining time but after 18 min of cutting, cutting force drop at 22.5 min of machining. During the experiment, it was noticed that less cutting force is achieved at cutting speed of 175 m/min in dry condition but in MQL condition, less cutting force is achieved at cutting speed of 225 m/min. MQL condition increases the cutting capability during high cutting speed.

Figure 4.6 (c) shows that high cutting speed reduces the tool life and increase the tool wear. At cutting speed of 250 m/min, cutting forces reaches to 802.2916 N after the third cut of 13.5 min of cutting operation which break the tool tip during dry condition. High cutting speed is not suitable for dry cutting because it creates high cutting force during cutting which decrease the tool life of the tool, but in MQL condition, the tool is capable to work with high cutting speed which increase the cutting ability.

During experiment, it was noticed that CVD 4230 gives good results at cutting speed 225 m/min in MQL machining. However, MQL condition achieves less cutting force in all cutting speed as compared to the dry machining, but it achieves less cutting force at cutting speed 225 m/min. This shows that MQL condition increases the machining capability to work under high cutting speed. Normally CVD 4230 is used for high cutting speed due to its coating thickness which increase the cutting capability. MQL condition provides good result as compared to dry condition in all cutting speed.

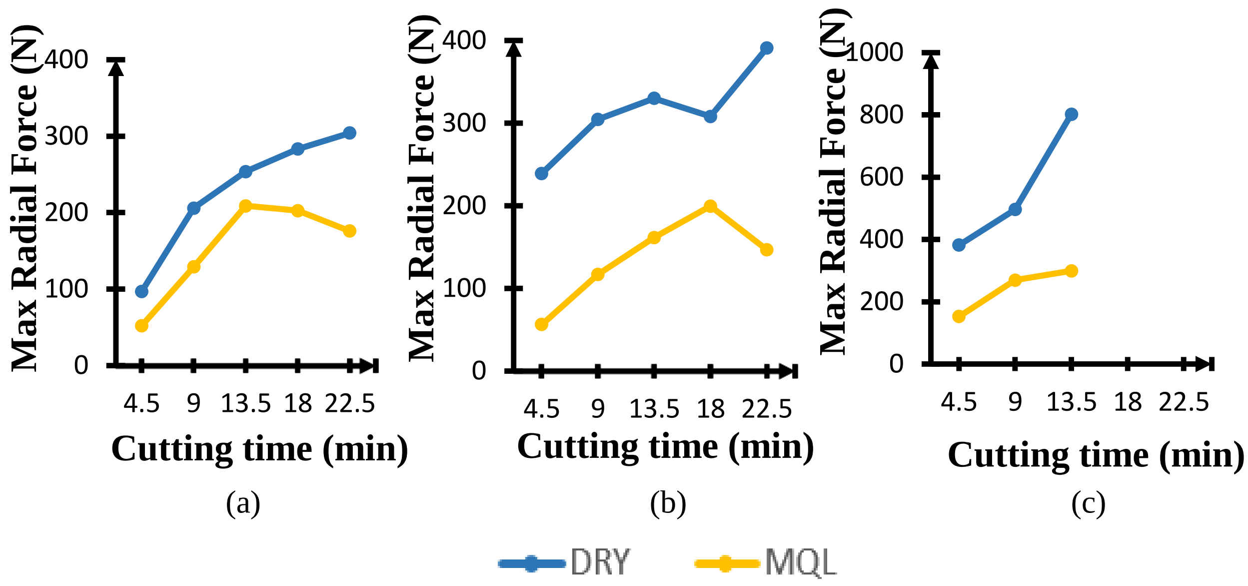


Figure 4.6: Cutting force result of the inserts after 22.5 min under fixed conditions (f=12 mm/min, doc= 1 mm) at a different cutting speed (A) at 200 m/min, (B) at 225 m/min, (C) at 250 m/min.

4.2.6 Comparison between CVD 4230 and CVD 4240 inserts

The experiments were performed in a five repeated passes at constant feed rate of 12mm/min, depth of cut of 1 mm, and varying cutting speed of 200, 225 m/min in every work piece of analysis the maximum radial forces which are acted on the work piece during the cutting. The experiments were conducted in MQL (minimum quantity lubrication) and dry lubrication as well as compared the performance of the different CVD inserts in these two machining conditions. The examinations were first done with CVD 4240 inserts and it is also known as CVD tool A which measures the maximum radial forces. Similar operation is done with CVD 4230 (CVD tool B) inserts. In this study, cutting length of the workpiece is 55 mm and measure the max radial forces in interval of every 4.5 min till 22.5 min.

Results showed that CVD 4240 achieves less cutting force at cutting speed of 200 m/min during dry condition but in MQL condition, it achieves less cutting force at cutting speed of 225 m/min. Similarly, in CVD 4230 it achieves less cutting force at 200 m/min cutting speed during dry condition, whereas in MQL machining, it achieves less cutting forces at 225 m/min. MQL machining reduces the cutting forces as cutting speed increases. It is very effective for the high speed machining. CVD 4230 provides good result over the CVD 4240 at cutting speed of 200, 225 m/min as shown in Fig. 4.7 under MQL condition. The results show that CVD 4230 insert generate less radial force as compared to the CVD 4240 inserts due to the larger coating thickness of the insert. So it has an ability to work under high cutting speed.

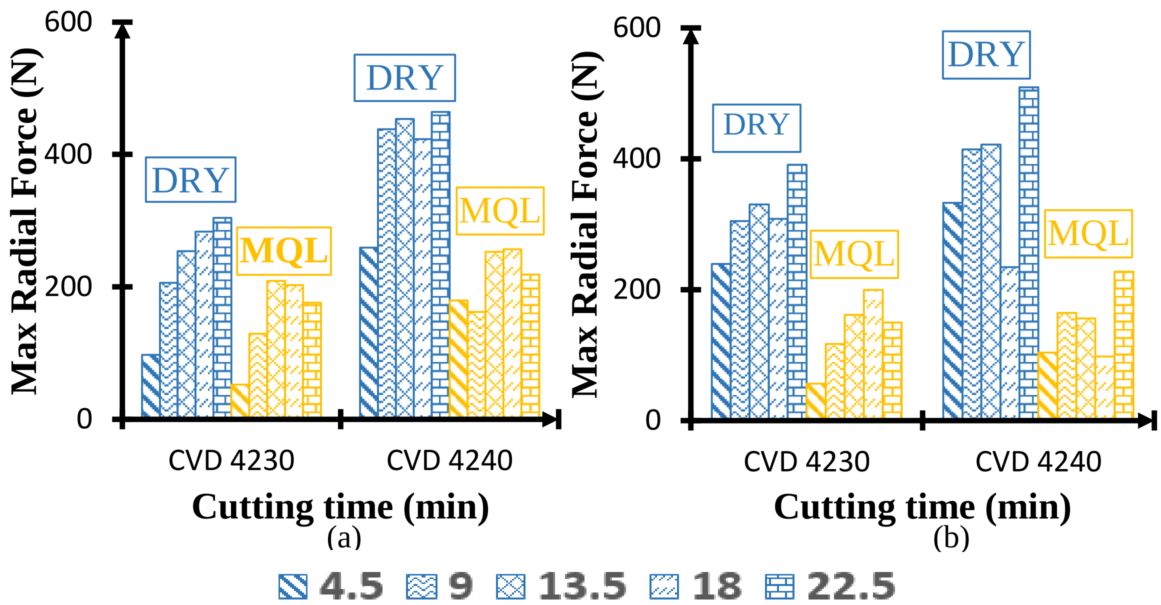


Figure 4.7: Maximum Radial cutting forces of CVD 4230 and CVD 4240 under the dry and MQL condition at fixed f = 12 mm/min, doc = 1mm under variable cutting speed (a) Vc = 200 m/min (b) Vc = 225 m/min

4.2.7 Comparison between PVD and CVD inserts

Figure 4.8 shows the result of comparative study of PVD tool A and CVD tool A to evaluate the performance of these carbide coated inserts under the different cutting speed at fixed feed rate and depth of cut. PVD inserts generate less cutting force as compared to the CVD inserts under both dry and MQL conditions as shown in Fig 4.8 (a). PVD inserts experience the catastrophic failure after the third cut of 13.5 min cutting due to the thin coating whereas CVD coating has thick coating which has the ability to cut the material at high cutting force. In MQL machining, less cutting force is generated on both PVD and CVD tool as compared to the dry condition. PVD inserts achieve less cutting force as compare to the CVD inserts due to its thin coating which has the ability to generate less cutting force during cutting operation, but it also fails between the cutting operations at a cutting speed of 175 m/min. Whereas CVD has thick coating which generates high cutting force as well as also increase the ability of a tool to cut the material under high cutting force. Figure 4.8 (b) shows that at high cutting speed i.e. Vc = 200 m/min, then no failure occurs during the cutting operation in PVD insert. PVD insert provides less cutting force under dry and MQL condition because it has a thin coating whereas CVD inserts has thick coating which increase the cutting force during cutting operation. MQL condition provides better results as compared to the MQL machining.

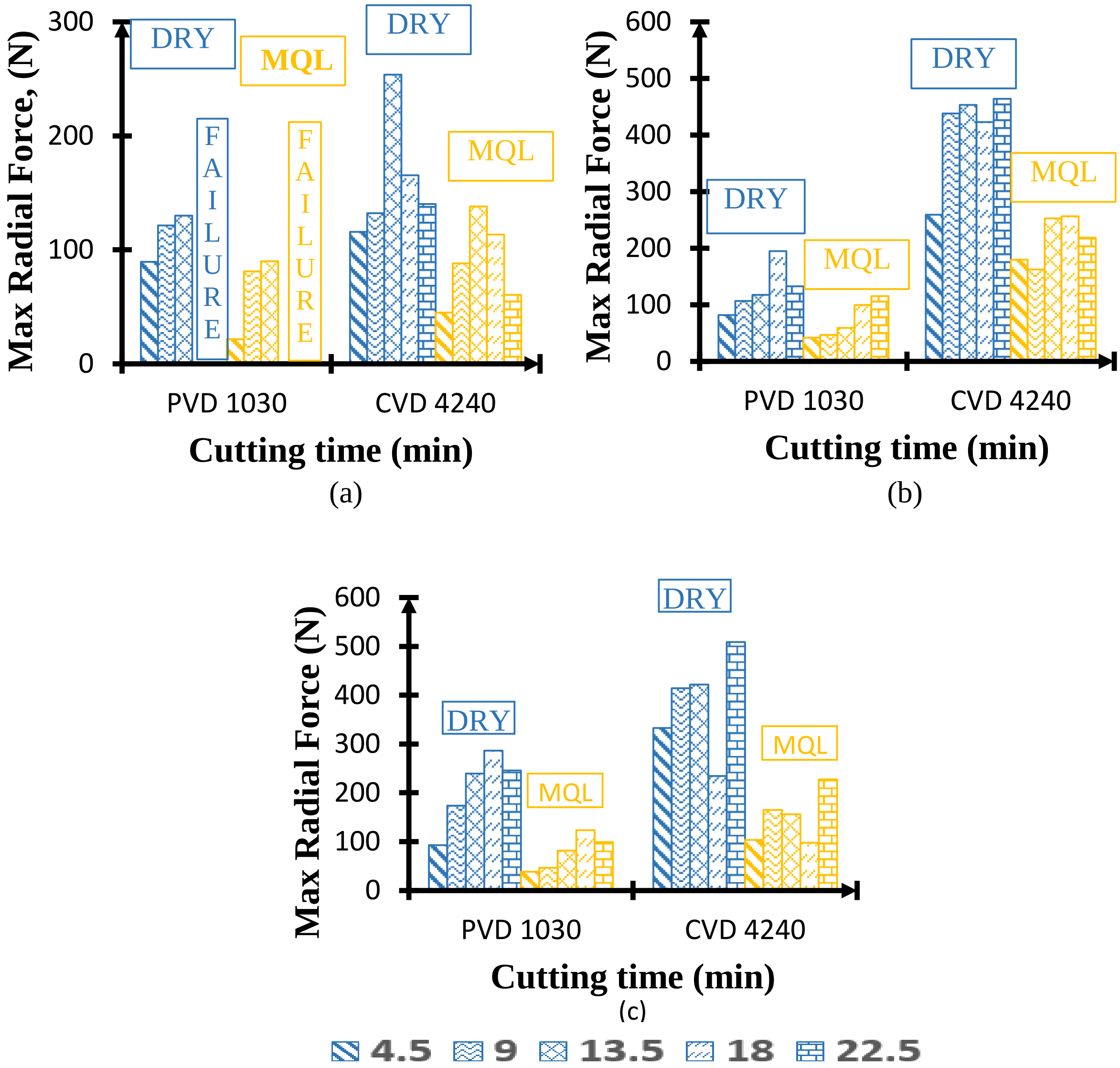


Figure 4.8: Maximum Radial cutting forces of PVD tool A and CVD tool A under dry and MQL at fixed f=12 mm/min, doc=1mm and variable cutting speed (a) Vc = 175 m/min (b) Vc = 200 m/min (c) Vc = 225 m/min

4.2.8 Effect of process parameters

In this study, the cutting speed varying at fixed depth of cut and feed rate is been analyzed. The effect of varying cutting speed is measured under milling operation during dry and MQL condition. During experiment, it was noticed that MQL machining generates less cutting force during cutting operation as compared to the dry condition. PVD inserts achieved less cutting force due to the thin coating whereas CVD inserts has thick coating, so it generates high cutting force. Cutting forces increases as the cutting speed increases in dry condition but in MQL condition less cutting force is achieved, so MQL machining increases the capability of tool to work at high cutting condition.

Table 4.1: Cutting Force of different CVD and PVD inserts under different cutting condition at fixed feed rate = 12mm/min, depth of cut = 1mm and varying speed.

PVD _1025					
V = 150 m/min		V = 175 m/min		V = 200 m/min	
DRY	MQL	DRY	MQL	DRY	MQL
60.4591	35.038	283.1031	30.7065	57.9	29.6
90.162	39.9259	347.5162	36.3856	70.155	25.52
110.7018	55.91732	378.7387	48.22903	118.1785	49.033
128.1972	40.6627	450.7552	56.29978	190.9501	88.24163
92.13497	393535	557.6172	60.82133	163.644	130.2084

PVD _1030					
V = 175 m/min		V = 200 m/min		V = 225 m/min	
DRY	MQL	DRY	MQL	DRY	MQL
89.56	21.5	81.82	41.79	92.682	37.935
121.44	80.17	106.61	46.47	173.66	46.175
130	90	117.434	58.80	239.23	81.62
-	-	194.71	99.69	286.497	123.513
-	-	132.381	115.353	245.562	99.216

CVD _4240					
V = 175 m/min		V = 200 m/min		V = 225 m/min	
DRY	MQL	DRY	MQL	DRY	MQL
115.83	45.01	259	179.39	332.60	103.5342
136.09	88.24	438.24	162.08	414.06	164.57
253.61	138.09	453.51	252.81	421.52	155.85
165.51	113.50	423.06	256.57	234.30	97.71
140.28	60.51	464.07	218.46	509.02	227.61

CVD_4230					
V = 200 m/min		V = 225 m/min		V = 250 m/min	
DRY	MQL	DRY	MQL	DRY	MQL
96.98	52.12	239.15	56.28	382.2031	152.77
205.93	128.96	304.68	116.88	495.9685	269.124
253.72	208.83	330.02	161.57	802.2916s	299.2649
283.19	202.51	308.16	199.64	-	-
304.31	175.99	390.83	146.73	-	-

4.3 Tool Wear Measurement

The mechanism involved in the analysis of tool wear is abrasion, adhesion, and diffusion wear. Tool wear mainly depend upon the cutting condition (speed, feed and depth of cut), work material, machining condition (dry and MQL) and tool material. When tool comes in contact with the workpiece then friction force is generated between the flank face and the workpiece. Mainly flank wear occurs due to adhesion and abrasion wear. In adhesion wear, high amount of normal mode shear stress act on the tool. This wear mainly occurs during the built-up-edge. When the built-up-edge has appeared on the tool surface and it tried to tear out the tool material.

Abrasion wear mainly occurs due to the relative motion between the two surfaces. In this study, the experiment is done in the dry as well as MQL condition. In dry conditions, high friction force, generate between the tool and workpiece but in MQL condition, high pressure lubrication oil is injected with high pressure air directly on the cutting zone which help to reduce the friction force between the tool and machine. This is the main reason for less tool wear in MQL condition as compared to the dry condition as shown in Table 4.2 [Tool Wear results under varying cutting speed at fixed depth of cut and feed rate (f=12 mm/min, doc=1 mm)] and tool wear microstructures are shown in appendix 2.

4.3.1 Tool Wear Progression of PVD 1025 inserts

At this stage, tool wear is measured on PVD 1025 inserts at constant feed rate of 12mm/min, depth of cut of 1 mm, and cutting speed of 150, 175, 200 m/min. The experiment is performed in five repetition cut. Tool wear is measured in intervals of every 4.5 min till 22.5 min of machining, after every cut of 55 mm measure the individual performance of PVD 1025 coated inert. All readings were collected for the tool wear and compared for the performance of the insert on the different machining (Dry and MQL) condition as shown in Fig. 4.9.

Figure 4.9 (a) shows that tool wear during cutting operation at cutting speed of 150 m/min. In this cutting speed, there is a little bit difference between the performance of a dry and MQL condition. MQL condition achieves less tool wear as compared to the dry condition. High tool wear generates at cutting speed of 175 m/min during dry condition, whereas in MQL condition, less tool wear generates as shown in Fig 4.9 (b). Performance of PVD 1025 insert in MQL cutting during cutting speed of 175 m/min provides better results than dry condition. Tool life also increases in MQL condition as well as it also increases the cutting ability of the tool.

Figure 4.9 (c) shows that, less tool wear occurs at cutting speed of 200 m/min and tool wear is increased with increase of cutting time. MQL machining achieved less tool wear as compared to the dry condition. At cutting speed of 200 m/min less tool wear occur in a MQL condition, whereas in dry condition less tool wear is occurring at cutting speed of 150 m/min. Thus, MQL condition increases the machining capability at high cutting speed. Hence MQL machining is recommended for high cutting speed whereas dry condition is not suitable for high cutting speed. Normally PVD 1025 is used for light cut. But in MQL condition, it can be used for high cutting speed.

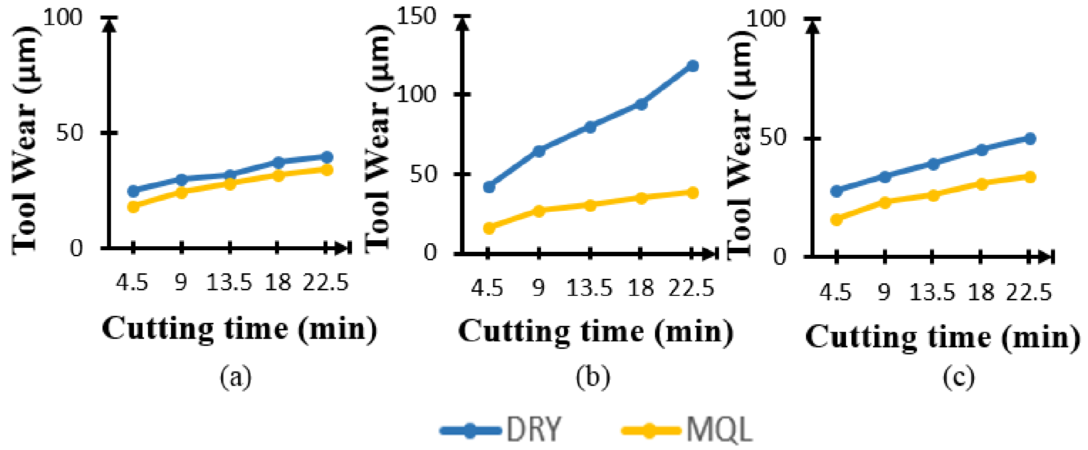
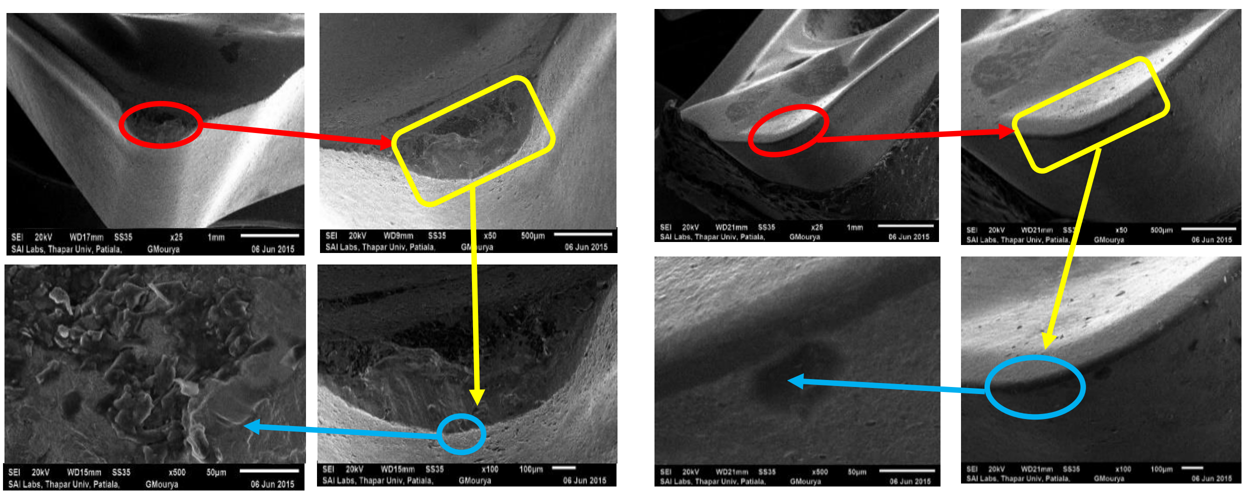


Figure 4.9: Tool wear result of the inserts after 22.5 min under fixed conditions (f=12 mm/min, doc= 1 mm) at a different cutting speed (a) at 150 m/min, (b) at 175 m/min, (c) at 200 m/min.

Tool wear also measured by the SEM analysis. Figure 4.10 (a) shows that SEM microstructure of flank wear under dry condition on the tool PVD 1025. After machining 22.5 min under dry condition at cutting speed of 175 m/min, adhesion and abrasion wear both occur on the flank face of the tool. Abrasion wears occur on the tip of the tool, whereas Adhesion wear occur by some distance from the tool tip. During MQL machining, there is no effect on the tool after machining 22.5 min. No abrasion and adhesion, wear are found on the flank face of the tool at cutting speed 175 m/min.



(a) (b)

Figure 4.10: SEM result of the tool (a) dry condition (b) MQL condition.

4.3.2 Tool Wear Progression of PVD 1030 inserts

Figure 4.11 (a) shows that tool experience catastrophic failure during dry condition at cutting speed of 175 m/min. Performance of PVD tool in cutting speed of 175 m/min in both conditions is good, but in dry condition tool fails after the third cut of machining due to the thin coating. Whereas in MQL condition, tool wear is comparatively less as compared to the dry condition.

Figure 4.11 (b) shows that PVD 1030 performed better at cutting speed of 200 m/min as compared to the cutting speed of 175 m/min in both dry and MQL conditions. MQL condition provides outstanding performance at high cutting speed and also reduce the tool wear as well as increase the tool life. PVD insert provides good result at cutting speed of 225 m/min as compared with the dry condition as shown in Fig 4.11 (c). In this experiment it was observed that at cutting speed (Vc = 200 m/min) provides good result in dry as well as MQL condition. Hence, MQL machining provides better results in dry conditions.

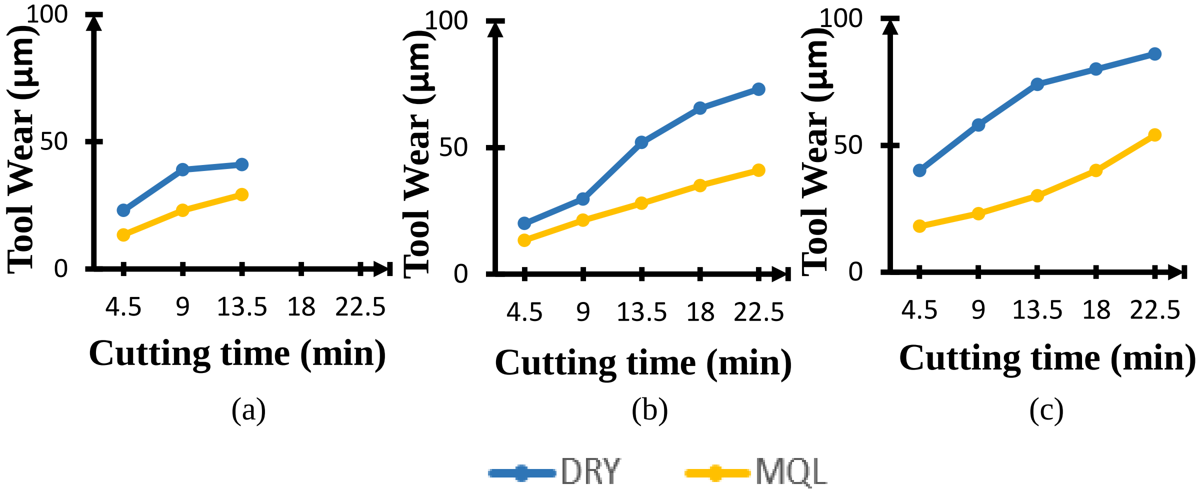
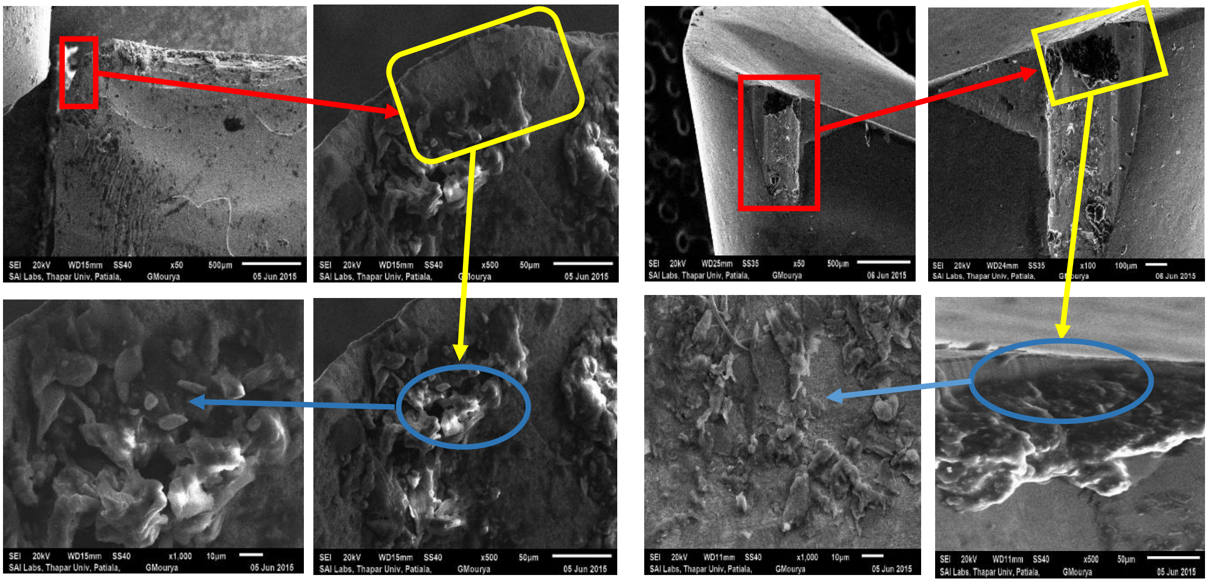


Figure 4.11: Tool wear result of the inserts after 22.5 min under fixed conditions (f=12 mm/min, doc= 1 mm) at a different cutting speed (a) at 175 m/min, (b) at 200 m/min, (c) at 225 m/min.

PVD 1030 insert coating is removed during dry operation of cutting speed of 175 m/min. After cutting for 13.5 min, its coating removed from the inserts due to the formation of the chip and generates high temperature on the insert. Due to the removal of the coating from the insert it is difficult to predict wear which occurs during cutting operation as shown in Fig 4.12 (a) but in MQL condition both adhesion and abrasion wear is generated at the tool tip at cutting speed of 225 m/min. Abrasion wear was generated at the tool edge, whereas adhesion wear was generated at some distance from the tool edge as shown in Fig 4.12 (b). This SEM result shows the wear condition after cutting of 22.5 min.



(a) (b)

Figure 4.12: SEM result of the tool (a) dry condition at Vc = 175 m/min (b) MQL condition at Vc = 225 m/min

4.3.3 Tool Wear comparison between PVD 1025 and PVD 1030 inserts

Tool wear is measured on PVD tool A (insert 1030) and PVD tool B (insert 1025) inserts at constant feed rate of 12mm/min, depth of cut of 1 mm, and cutting speed of 175, 200 m/min. The experiment was performed in five repetition cut. Tool wear was measured in intervals of every 4.5 min till 22.5 min of machining, after every cut of 55 mm the performance of PVD tool A and PVD tool B coated insert was measured. PVD tool A has TiAlN+TiN coating and PVD tool B has TiCN+TiN coating. The result shows that PVD tool A performed better at cutting speed of 175 m/min in dry condition whereas PVD tool B performed well in MQL condition as shown in Fig. 4.13. PVD tool B performed better at cutting speed of 200 m/min in both dry as well as MQL condition. So for high cutting PVD tool B was preferred for machining. MQL condition provides less tool wear in all cutting conditions at all machining time.

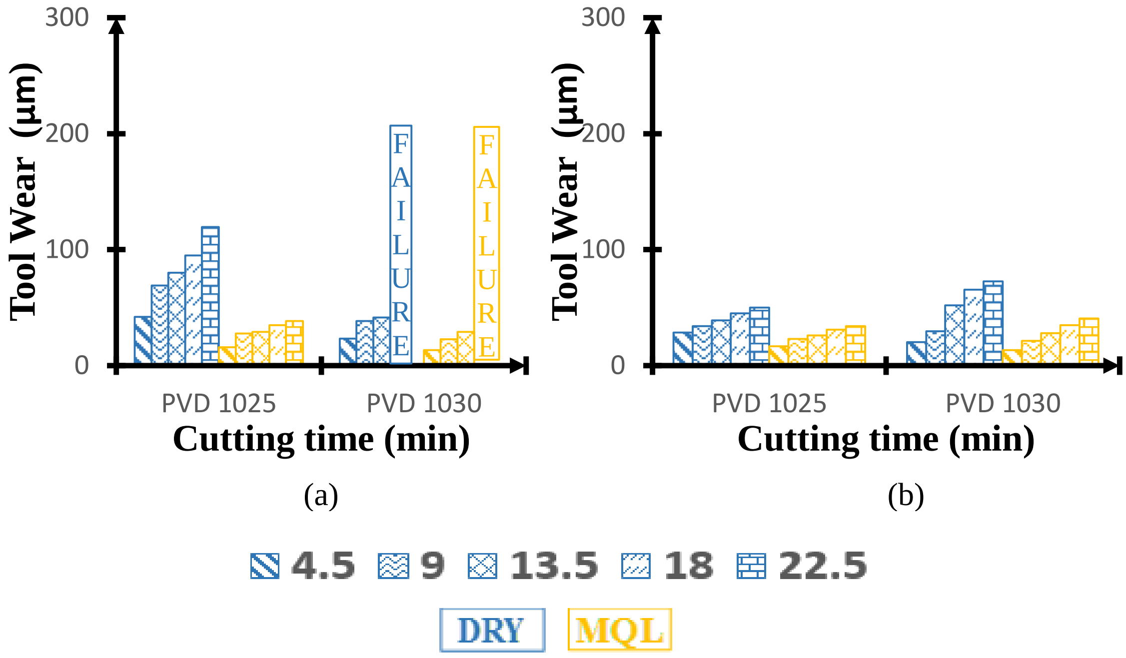


Figure 4.13: Tool wear result of the inserts after 22.5 min under fixed conditions (f=12 mm/min, doc= 1 mm) at a different cutting speed (a) at 175 m/min, (b) at 200 m/min.

4.3.4 Tool Wear Progression of CVD 4230 inserts

Tool wear was measured on CVD 4230 inserts at constant feed rate of 12mm/min, depth of cut of 1 mm, and cutting speed 200, 225, 250 m/min. The experiment was performed in five repetition cut. Tool wear was measured in intervals of every 4.5 min till 22.5 min of machining, after every cut of 55 mm measure the individual performance of CVD 4230 coated inert in different cutting speed. All reading of the tool wear were collected and compared for the performance of the coated inserts on the different machining (Dry and MQL) condition as shown in Fig. 4.14. The result shows that CVD 4230 gives good results at cutting speed of 225 m/min in both dry conditions as well as in MQL machining condition, but less tool wear occurs on the tool during MQL machining as compared to the dry condition. This shows that MQL condition increases the machining capability cutting. Figure 4.14 (c) shows that when machining is done under a high condition then tool fails after 13.5 min cutting operation. However result shows that in dry condition, CVD 4230 doesn't able to work at a high cutting speed, but in MQL condition, it works under the high cutting speed. So CVD 4230 is recommended for high speed cutting under the MQL condition. MQL condition provides good result as compared to dry condition in all cutting speed.

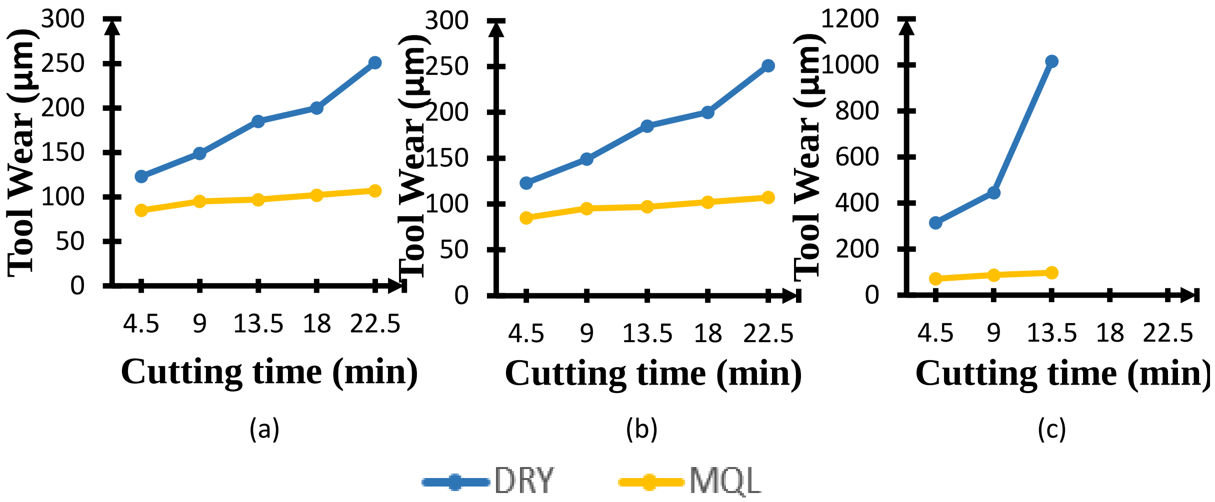


Figure 4.14: Tool wear result of the inserts after 22.5 min under fixed conditions (f=12 mm/min, doc= 1 mm) at a different cutting speed (a) at 200 m/min, (b) at 225 m/min (c) at 250 m/min

SEM (scanning electron microscope) is used to analyze the tool wear after 22.5 min of machining. Adhesion and Abrasion wear are found in the tool tip during the cutting operations as observed in Fig. 4.15. Abrasion wear occurs during dry condition at cutting speed of 250 m/min whereas adhesion wear as well as abrasion wear occurs during MQL condition.

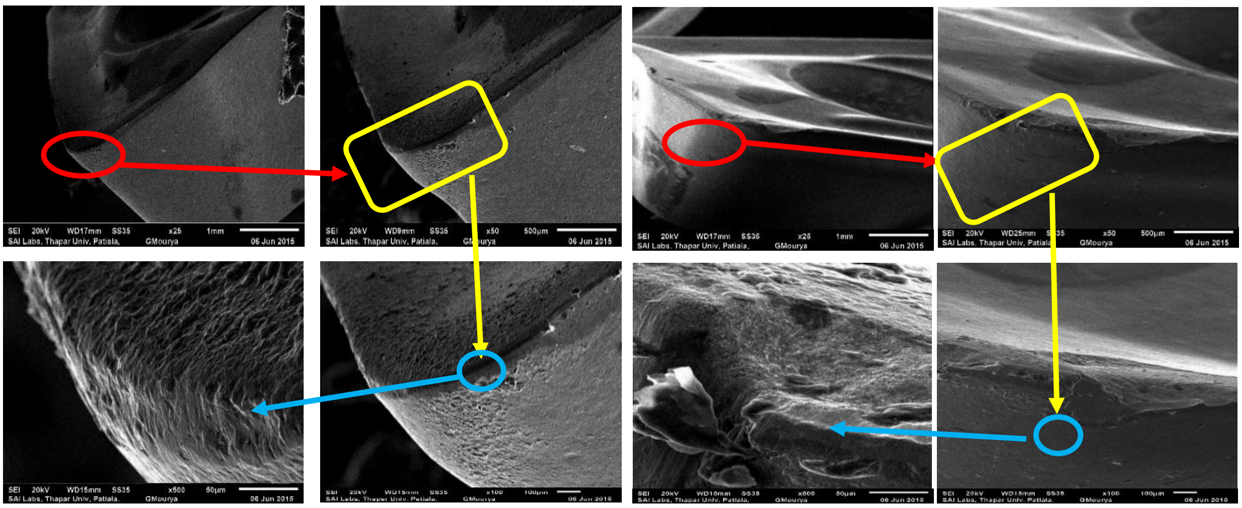


Figure 4.15: SEM result of the tool (a) dry condition at Vc = 250 m/min (b) MQL condition at Vc = 250 m/min.

4.3.5 Tool Wear Progression of CVD 4240 inserts

Tool wear is measured on CVD 4240 inserts at constant feed rate of 12mm/min, depth of cut of 1 mm, and cutting speed 175, 200, 225 m/min. The experiment is performed in five repetition cut. Tool wear is measured in intervals of every 4.5 min till 22.5 min of machining, after every cut of 55 mm measure the individual performance of CVD 4240 coated inert in different cutting speed. All the readings were collected for the tool wear and compared with the performance of the coated inserts on the different machining (Dry and MQL) condition as shown in Fig. 4.16.

The result shows that CVD 4240 gives good results at cutting speed of 175 m/min in dry condition, whereas in MQL condition, it achieves less tool wear at cutting speed of 225 m/min but after the third cut of 13.5 min machining tool wear increases rapidly. The MQL condition increases the machining capability of cutting. However it shows that in dry condition cutting capability of the tool gets decreased whereas in MQL condition, cutting ability is increased and it easily work under higher cutting speed. MQL condition provides good result as compared to dry condition in all cutting speed.

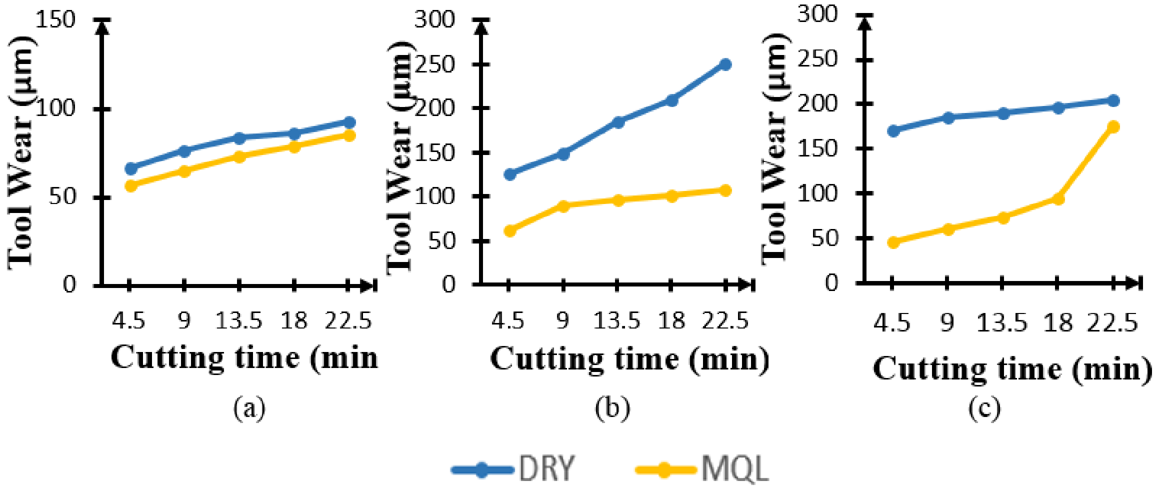


Figure 4.16: Tool wear result of the inserts after 22.5 min under fixed conditions f=12 mm/min, doc=1 mm (a) at Vc = 175 m/min (b) at Vc = 200 m/min (c) at Vc = 225 m/min

SEM (scanning electron microscope) is also used to analyze the tool wear after 22.5 min of machining. After SEM analyses, it observed that adhesion and abrasion wear are found in the tool tip as shown in Fig. 4.17. Abrasion wear is occur during dry condition at cutting speed of 225 m/min whereas adhesion wear is occur during MQL condition.

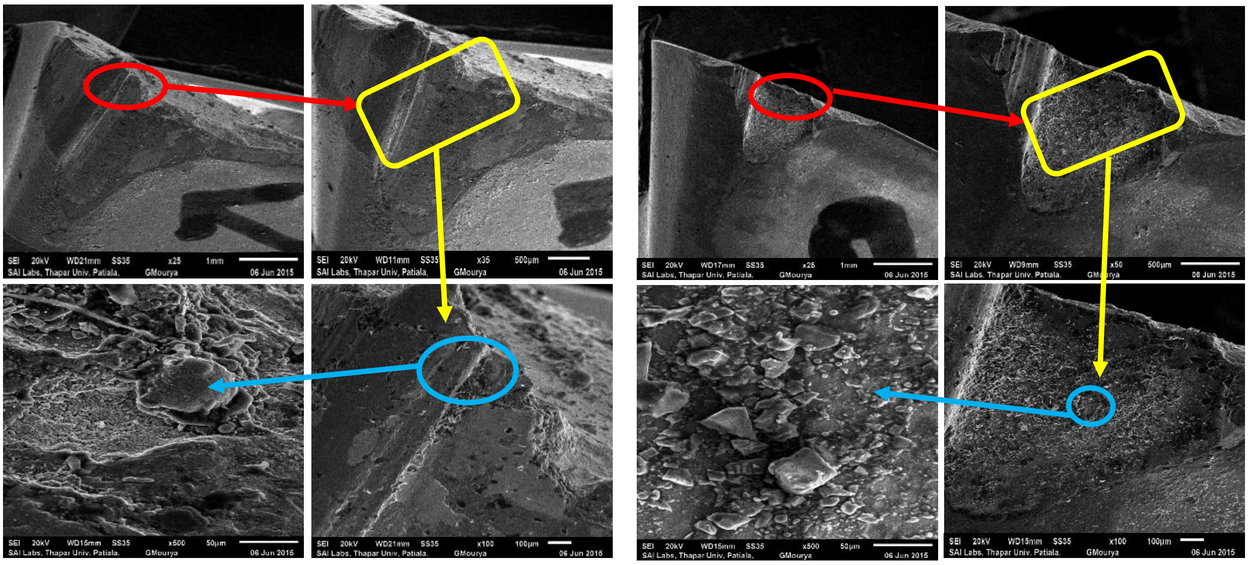


Figure 4.17: SEM result of the tool (a) dry condition at Vc = 175 m/min (b) MQL condition at Vc = 225 m/min.

4.3.6 Tool Wear comparison between CVD 4230 and CVD 4240 inserts

Tool wear was measured on CVD 4240 and CVD 4230 inserts at constant feed rate of 12 mm/min, depth of cut of 1 mm, and cutting speed of 200,225 m/min. The experiment was performed in five repetition cut. Tool wear was measured in intervals of every 4.5 min till 22.5 min of machining, after every cut of 55 mm, the performance of CVD 4240 and CVD 4230 coated inert was measured. All reading of the tool wear were collected and compared, and the performance of these coated inserts on the different machining (Dry and MQL) condition was observed. The result shows that CVD 4240 gives good results at cutting speed of 200 m/min in dry condition, whereas in MQL machining condition it gives good results at cutting speed 225 m/min. CVD 4230, less tool wear is occurred on the tool for cutting speed of 225 m/min in both dry condition and MQL machining. CVD 4230 provides less tool wear in cutting speed of 225 m/min in MQL condition as compared to the CVD 4240 as shown in Fig. 4.18. CVD 4230 provides a good result over the CVD 4240 at cutting speed of 225 m/min because CVD 4230 inserts improve quality of CVD 4240 inserts and also it has the ability to work under high cutting speed, as well as coating thickness is also thin as compared to the CVD 4240.

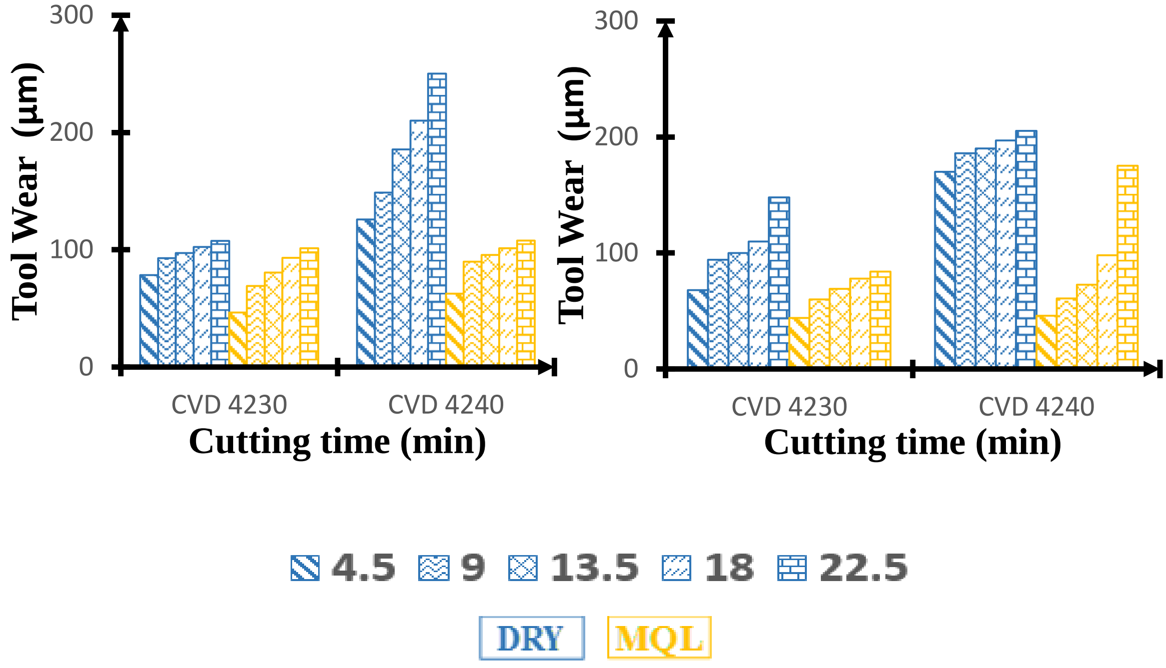


Figure 4.18: Tool wear result of the inserts after 22.5 min under fixed conditions f=12 mm/min, doc=1 mm (A) at Vc =200 m/min (B) at Vc 225 m/min

4.3.7 Tool Wear comparison between PVD and CVD inserts

Cutting capability of the tool was increased in the MQL condition as compared to the Dry condition. In dry conditions, CVD tool achieves less tool wear at cutting speed of 175 m/min, whereas in MQL condition less tool wear is achieved at cutting speed of 225 m/min but after machining 13.5 min, the tool abruptly wear out. It is observed MQL condition is very effective for high speed machining. In PVD insert, less tool wear is achieved in both conditions, but in MQL condition, less tool wear is occurred as compared to the dry as shown in Fig. 4.19. PVD insert gives the best result as compared to the CVD inserts under all cutting speed in MQL condition because PVD inserts has thin coating, but it experience the catastrophic failure at 175 m/min cutting speed whereas CVD inserts has thick coating, which increase the cutting ability under high cutting speed as well as different cutting condition. This shows that PVD 1030 inserts is not good for low cutting speed.

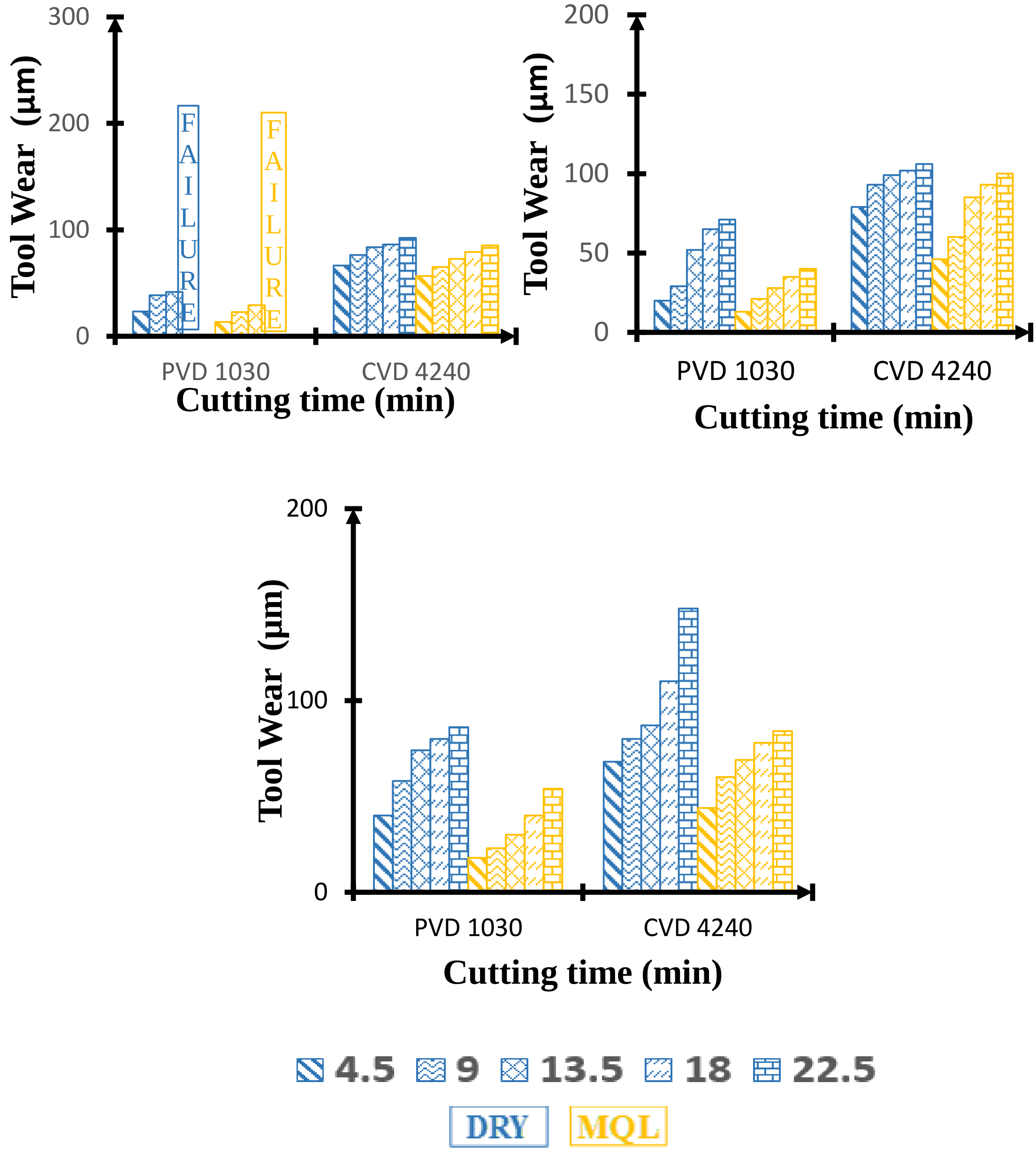


Figure 4.19: Tool wear result of the inserts after 22.5 min under fixed conditions (Vc = 200 m/min, f = 12 mm/min, doc = 1 mm).

4.3.8 Effects of Cutting Parameters and Lubrication on Tool wear

In this study, the cutting speed varying at fixed depth of cut and feed rate. The effect of varying cutting speed in the tool wear under milling operation during different cutting condition on different PVD and CVD inserts. During experiment, it is noticed that MQL machining reduce tool wear during cutting operation as compared to the dry condition. PVD inserts achieved less tool wear due to the thin coating whereas CVD inserts has thick coating, so it generates high tool wear. Tool wear doesn't depend on cutting speed, so it is not increases as the cutting speed increases but it depend on cutting time. Tool wear increases as the cutting time increases. MQL machining, provides good results in all machining condition such as dry as well as MQL.

Table 4.2: Tool Wear results under varying cutting speed at fixed depth of cut and feed rate (f=12 mm/min, doc=1 mm)

PVD 1030					
V = 175 m/min		V = 200 m/min		V = 225 m/min	
DRY	MQL	DRY	MQL	DRY	MQL
23.4	13.4	20.3	13.4	40	18
38.5	22.9	29.7	21.3	58	22
41.6	29.2	52	28	74	30
-	-	65	35	81.1	40.7
-	-	72.8	40.7	86	54

PVD 1025					
V = 150 m/min		V = 175 m/min		V = 200 m/min	
DRY	MQL	DRY	MQL	D RY	MQL
25	18.3	41.8	16.1	28.6	16.7
29.7	24.6	69.7	27.7	34.4	23
32.3	28.1	80.2	29.2	39	26
37	32.3	95.5	34.9	45	31
41.2	34.3	119.6	38.5	50	34

CVD 4240					
V = 175 m/min		V = 200 m/min		V = 225 m/min	
DRY	MQL	DRY	MQL	DRY	MQL

66.6	56.7	125.9	62.5	170	45.8
76.5	65.1	148.7	90	185	61
83.8	72.8	186.7	95.7	190	72.8
86.4	79.1	210.1	101.4	197.1	95.2
92.6	85.3	250.1	108.4	205.4	175

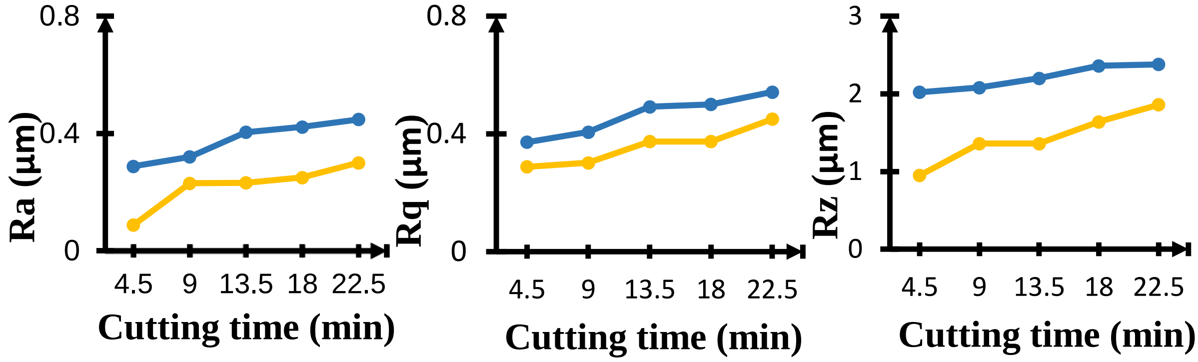
CVD 4230					
V = 200 m/min		V = 225 m/min		V = 250 m/min	
DRY	MQL	DRY	MQL	DRY	MQL
78.5	46.4	68	44	315	71
93	69.2	80	60	400	87
97.3	80.2	87	69	446.7	100.1
102.4	93.1	122.7	86.9	-	-
107.7	101.4	148	84	-	-

4.4 Surface roughness measurement

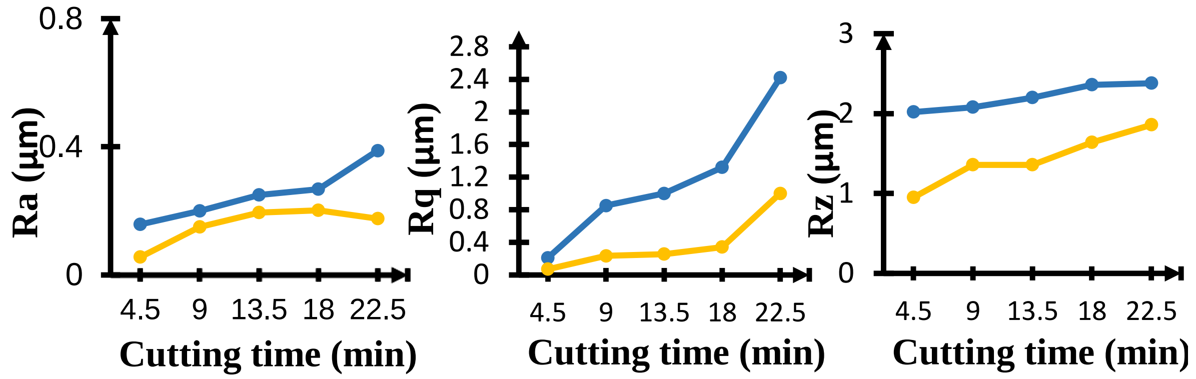
Surface roughness was evaluated by machining of the EN-31 material with a different coated carbide inserts under different machining condition such as dry and MQL machining. There are three factors which influence the surface roughness such as feed rate, cutting speed and nose radius. In this experiment, focused on the cutting speed and performed an experiment by varying cutting speed to see the effect of varying cutting speed on the surface roughness in dry and MQL condition as shown in Table 4.3 [Surface roughness results under varying cutting speed at fixed depth of cut and feed rate (f = 12mm/min, doc = 1mm)]. This study also shows the effect of coating thickness in the surface roughness of the machined surface. CVD 4240 and CVD 4230 both have same coating, but they're cutting capability are changing. CVD 4240 has recommended cutting speed is 260-270 m/min, whereas CVD 4230 inserts has improved quality of CVD 4240 so its recommended cutting speed is 310-320 m/min. This study was done at 30 degree angle of the nozzle from the workpiece. The experiments were performed in four different tools in different machining parameter to know the effect of varying speed on the surface of the workpiece during dry and MQL condition.

4.4.1 Surface roughness of PVD 1025 inserts

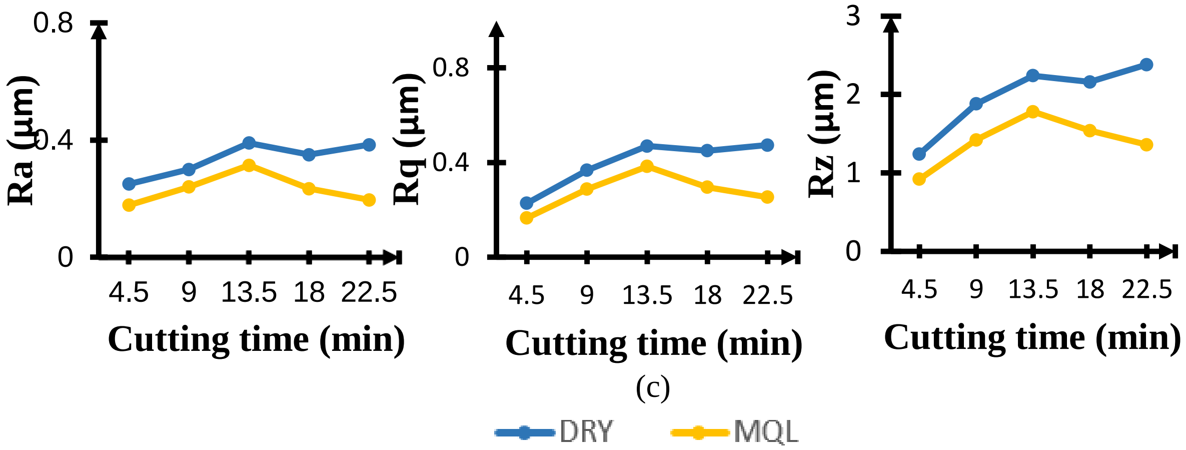
At this stage, surface roughness are measured on PVD tool A inserts at constant feed rate of 12mm/min, depth of cut of 1 mm, and varying cutting speed of 150, 175, 200 m/min. The experiment was performed in five repetition pass of an insert to know the performance of the PVD tool after every 4.5 min. The same process was continued till 22.5 min and reading was noted at every 4.5 min interval of the cutting operation. Experiments were performed on the inserts, all the readings of surface roughness Ra, Rq, Rz were noted and concluded that in MQL machining, good surface finish was achieved as compared to the dry machining. PVD 1025 provides a better surface finish at 175 m/min cutting speed during MQL condition as compared to the other surface roughness of the machined surface which has been provided by the cutting speed of 150 m/min as well as 175 m/min as shown in Fig.4.20. MQL provides better surface in all cutting speed because it helps to reduce the cutting force and increase the surface finish of the machined part.



(a)



(b)



(c)

Figure 4.20: Surface roughness (Ra, Rq, Rz) result of the inserts after 22.5 min under fixed condition (f=12 mm/min, doc= 1 mm) at cutting speed (a) 150 m/min (b) 175 m/min (C) 200 m/min.

4.4.2 Surface roughness of PVD 1030 inserts

At this stage, surface roughness are measured on PVD 1030 inserts at constant feed rate of 12 mm/min, depth of cut of 1 mm, and varying cutting speed of 175, 200, 225 m/min. The experiment was performed in five repetition pass of an insert to know the performance of the PVD tool after every 4.5 min. The same process was continued till 22.5 min and reading was noted at every 4.5 min interval of the cutting operation. Experiments performed on the insert as well as noted for all the readings of surface roughness Ra, Rq, Rz. At cutting speed of 225 m/min, good surface finish was achieved in both dry and MQL conditions among the rest two cutting speed. MQL provides a good surface finish as compare with the dry condition as shown in Fig 4.21. At 175 m/min cutting speed, less surface finish was achieved in dry as well as MQL condition as compared to higher cutting speed at of 225 m/min as shown in Fig 4.21 (a).

Hence, PVD 1030 inserts provide good surface at high cutting speed as shown in the experimental results. This insert found to be suitable for work under high cutting speed.

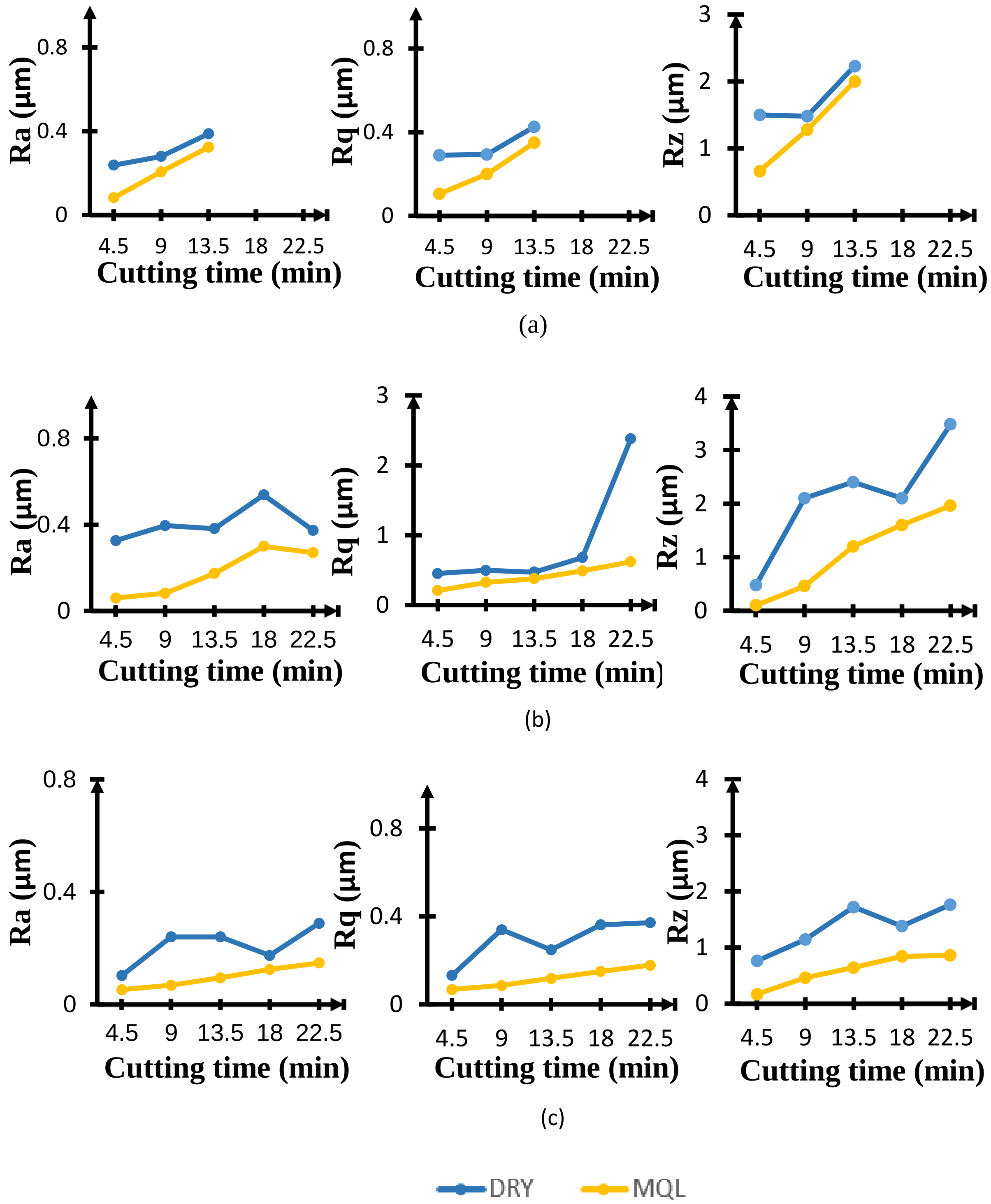


Figure 4.21: Surface roughness (Ra, Rq, Rz) result of the inserts after 22.5 min under fixed condition (f=12 mm/min, doc= 1 mm) at cutting speed (a) 175 m/min (b) 200 m/min (C) 225 m/min.

4.4.3 Comparison between PVD 1025 and PVD 1030 inserts

In this study, the experiment was performed in different cutting speed such as PVD 1030 performed the experiment at 175,200,225 m/min and PVD 1025 performed the experiment at 150,175,200 m/min. Among all these cutting speeds, two of these cutting speeds were same. So performance of the different PVD insert at same cutting speed compared. PVD 1025 performed better at 175 m/min cutting due to the TiCN+TiN coating under both cutting conditions such as dry and MQL condition as compared to the PVD 1030 inserts as shown in Fig 4.22. PVD 1030 insert failed during cutting operation at cutting speed 175 m/min under dry condition after 13.5 min machining as shown in Fig. 4.22 (a). PVD 1030 achieved good surface finish at 200 m/min cutting speed due to the TiAlN+TiN coating under MQL condition as compared to the PVD 1025 but in dry condition. PVD 1025 provides good result as compared to PVD 1030 as shown in Fig 4.22 (b). This PVD 1030 coating is harder and more stable than the PVD 1025 coating. Hence it is proved that TiAlN+TiN coating provides better results during MQL condition during high speed.

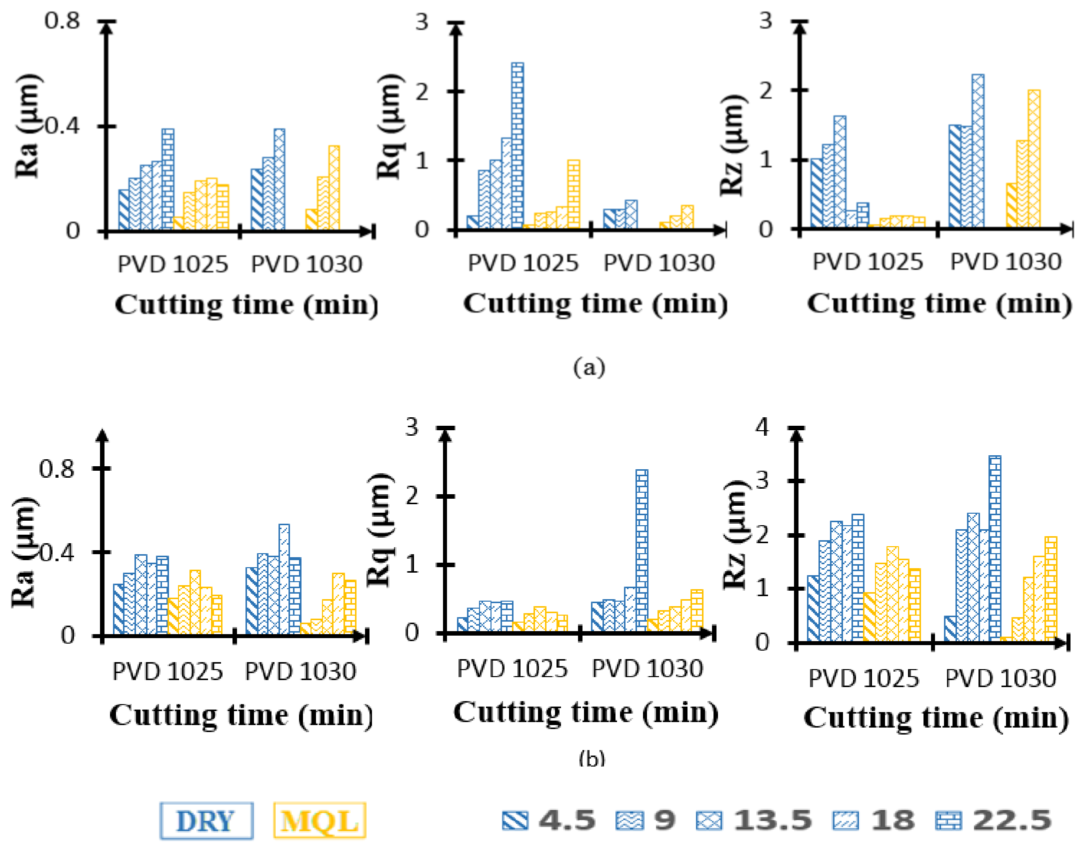
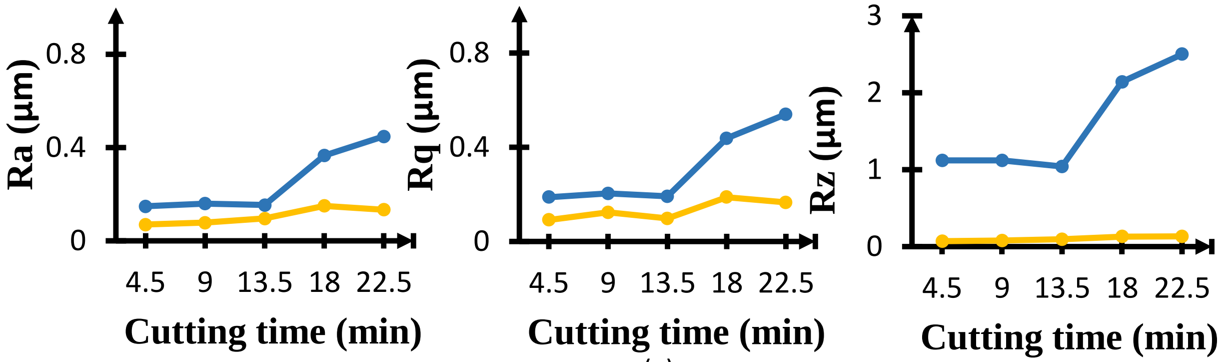


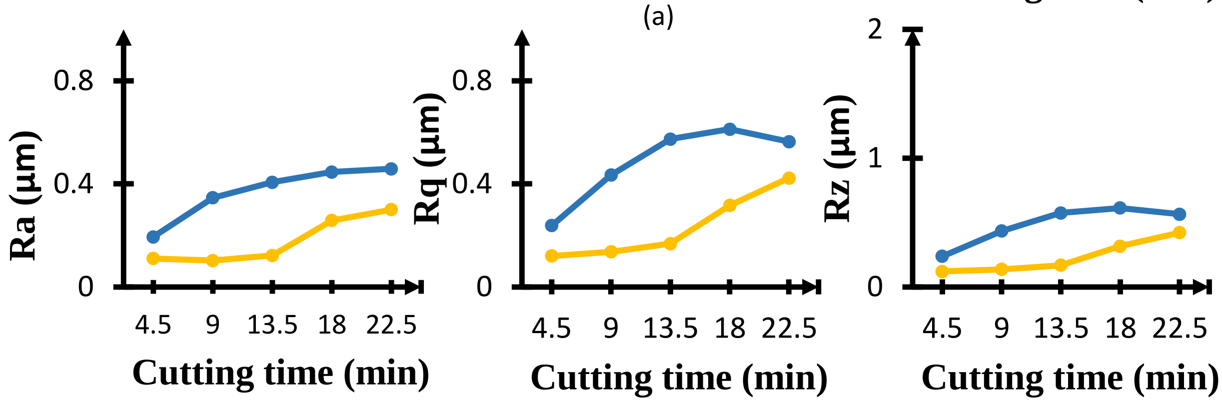
Figure 4.22: Surface roughness result of the inserts after 22.5 min under fixed condition (f=12 mm/min, doc= 1 mm) at variable cutting speed (a) Vc = 175 m/min (B) Vc = 200 m/min.

4.4.4 Surface roughness of CVD 4240 inserts

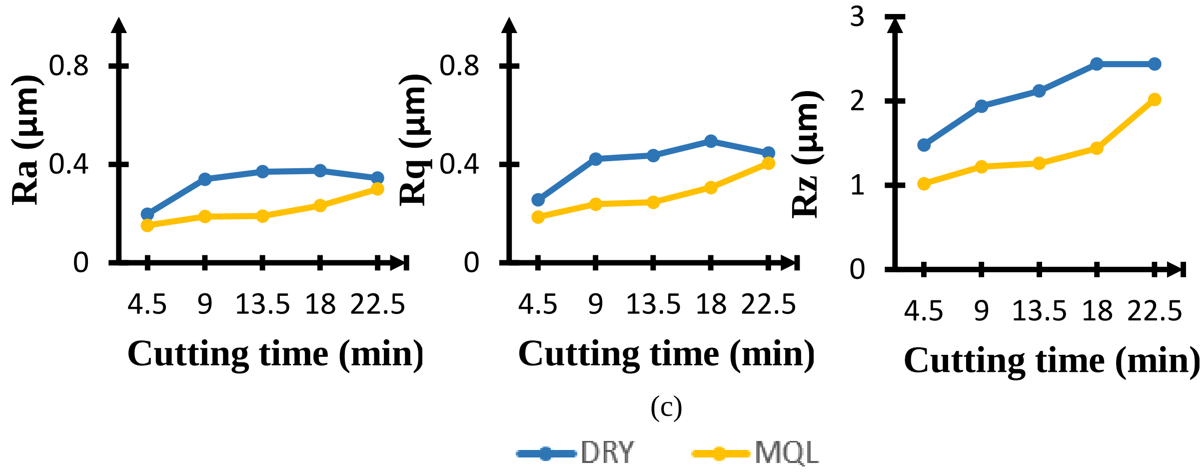
At this stage, surface roughness are measured on CVD 4240 inserts at constant feed rate of 12 mm/min, depth of cut of 1 mm, and varying cutting speed of 175, 200, 225 m/min. The experiment is performed in five repetition pass of an insert to know the performance of CVD tool after every 4.5 min. The same process is continuing till 22.5 min and reading is noted by every 4.5 min interval of the cutting operation. Experiments were performed on the insert as well as note all the readings of surface roughness Ra, Rq, Rz were noted. During the experiment, it was noticed that CVD 4240 provides initial good surface roughness at cutting speed 200 m/min than CVD 4230 as shown in Fig 4.23 (a) but after third cut, surface roughness value sudden increase in CVD 4240 in both dry and MQL conditions whereas in CVD 4230, surface roughness value gradually drop as cutting time increases. Figure 4.23 (b) shows that CVD 4230 provides good result at cutting speed 225 m/min in both cutting conditions as compared to the CVD 4240 inserts. Hence it was clear that at high cutting speed CVD 4230 is suitable because it insert thickness is higher than the CVD 4240. Thus, it can also say that insert thickness effect the quality of the machined part.



(a)



(b)



(c)

Figure 4.23: Surface roughness (Ra, Rq, Rz) result of the inserts after 22.5 min under fixed condition (f=12 mm/min, doc= 1 mm) at cutting speed (a) 175 m/min (b) 200 m/min (C) 225 m/min.

4.4.5 Surface roughness of CVD 4230 inserts

After performing the experiment measures the surface roughness of CVD 4230 at constant feed rate of 12 mm/min, depth of cut of 1 mm, and variable cutting speed of 200, 225, 250 m/min. Figure 4.24 (a) shows the surface roughness of the machined part at cutting speed of 200 m/min. Figure 4.24 (b) shows the effect of cutting speed of cutting speed 225 m/min on the surface of the machined part. At cutting speed of 250 m/min, surface roughness of the machined part is increased as shown in Fig. 4.23 (c). The experiment was performed in five repetition pass of an insert to know the performance of CVD 4230 after every 4.5 min. The same process was continued till 22.5 min and reading was noted by every 4.5 min interval of the cutting operation. Experiments were performed on the inserts as well as noted for all the readings of surface roughness Ra, Rq, Rz and concluded that in MQL machining, good surface finish is achieved as compared to the dry machining

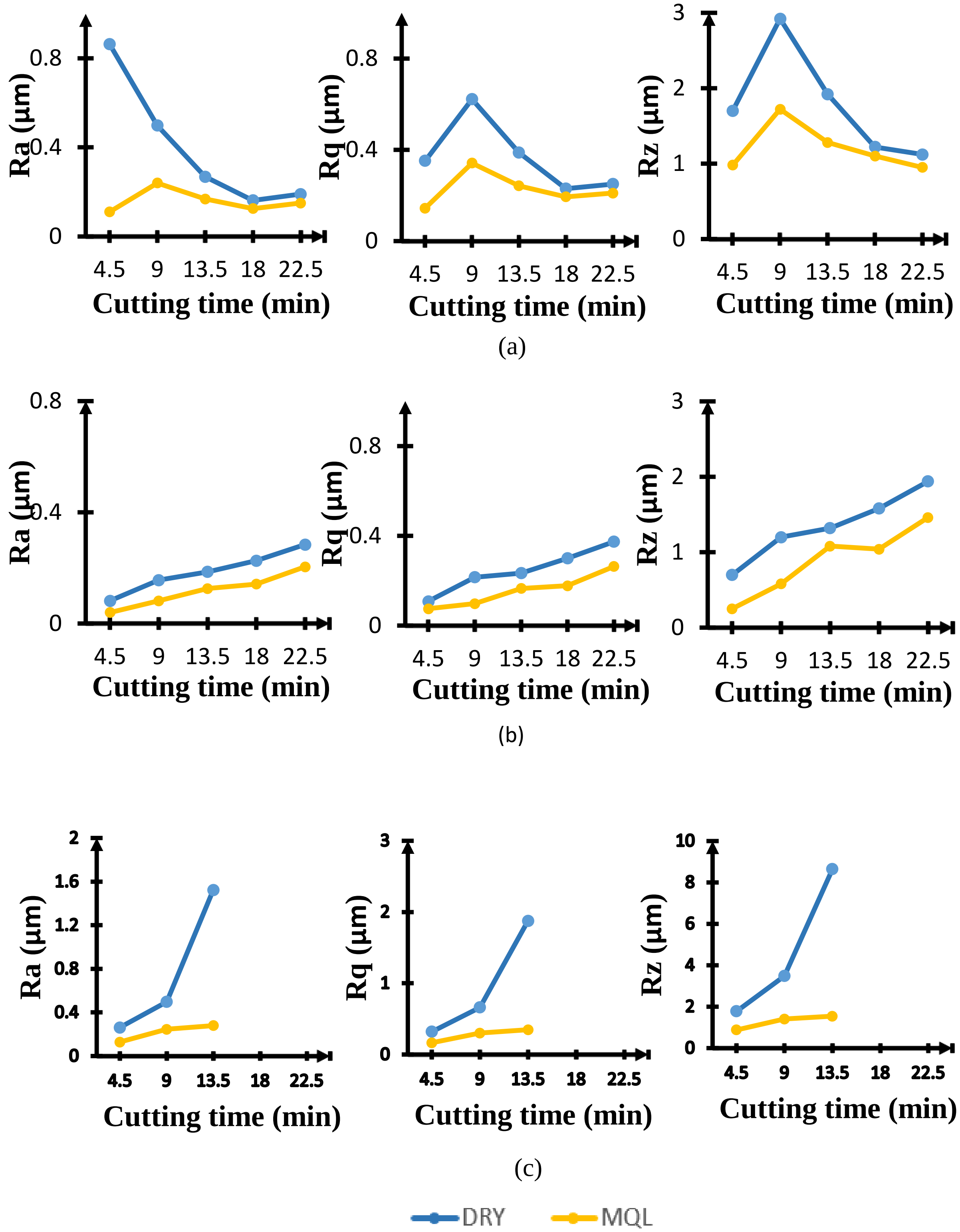


Figure 4.24: Surface roughness (Ra, Rq, Rz) result of the inserts after 22.5 min under fixed condition (f=12 mm/min, doc= 1 mm) at cutting speed (a) 200 m/min (b) 225 m/min (C) 250 m/min.

4.4.6 Comparison between CVD 4240 and 4230 inserts

Experiments performed on the inserts in different cutting speed in CVD 4240 and CVD 4230 such as cutting speed for CVD 4240 were 175, 200, 225 m/min and CVD 4230 were 200,225,250 m/min. Among all these cutting speed two cutting speed of the two inserts were same. So the comparison was done between CVD 4240 and CVD 4230 at cutting speed of 200,225 m/min. During investigation, it was observed that good surface was achieved by CVD 4230 at cutting speed 200 m/min as compare to the CVD 4240 during MQL machining as shown in Fig 4.25 (a). CVD 4230 also provides a better surface finish at cutting speed 225 m/min as compare to the CVD 4240 as shown in Fig 4.25 (b). CVD 4230 gives a good surface finish at both cutting speed of 200,225 m/min as compared to the CVD 4240 because CVD 4230 has high insert thickness value as compared to the CVD 4240. So it is noticed that insert thickness effect the performance of the tool as well as the quality of the machined part.

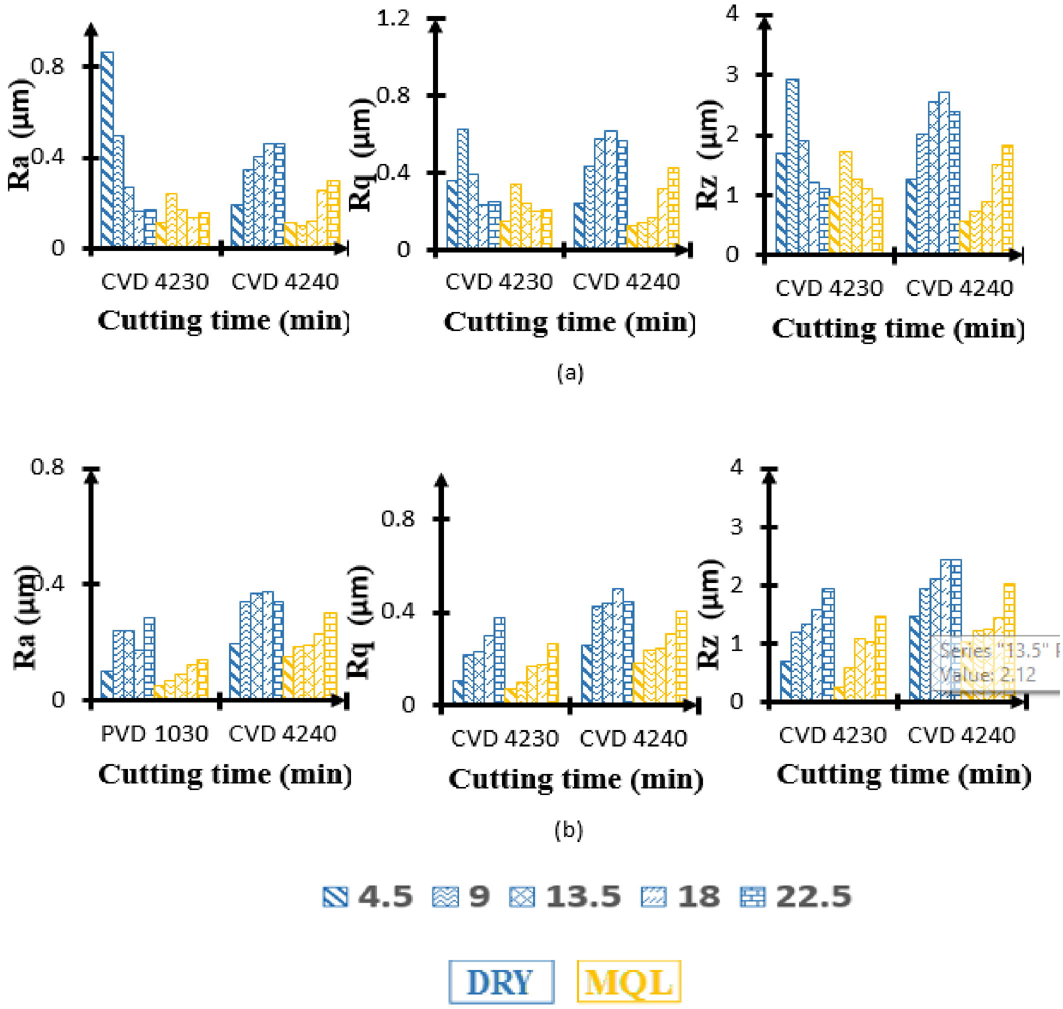
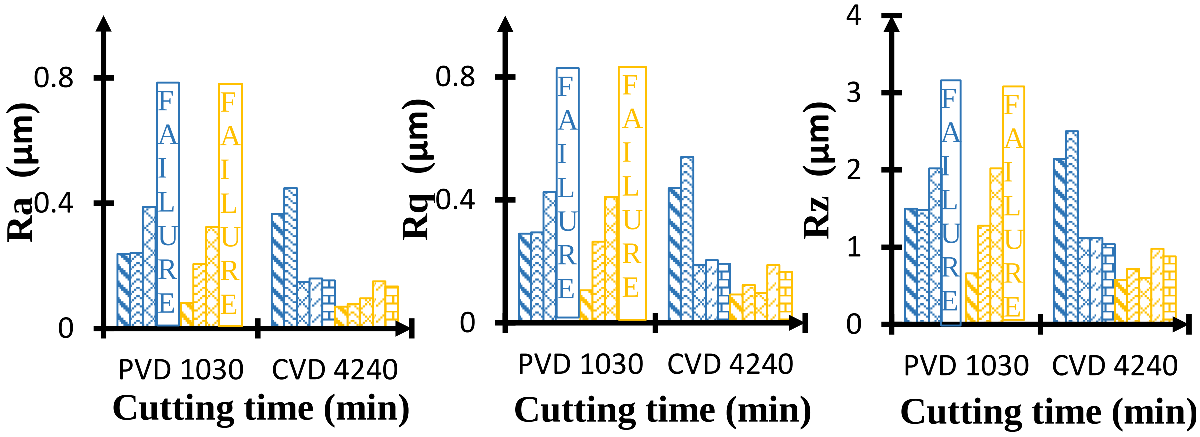


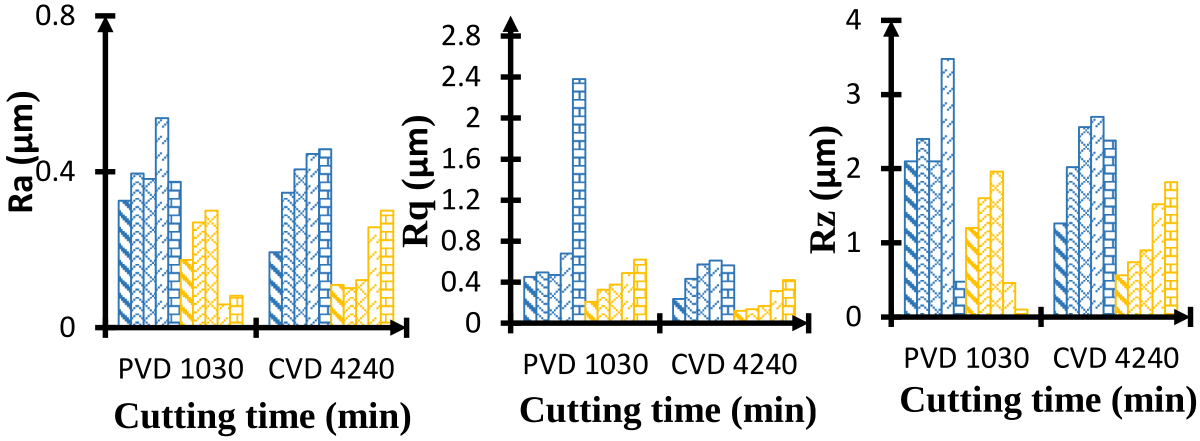
Figure 4.25: Surface roughness (Ra, Rq, Rz) result of the inserts after 22.5 min under fixed condition (f=12 mm/min, doc= 1 mm) at cutting speed (a) 200 m/min (b) 225 m/min

4.4.7 Comparison between PVD and CVD inserts

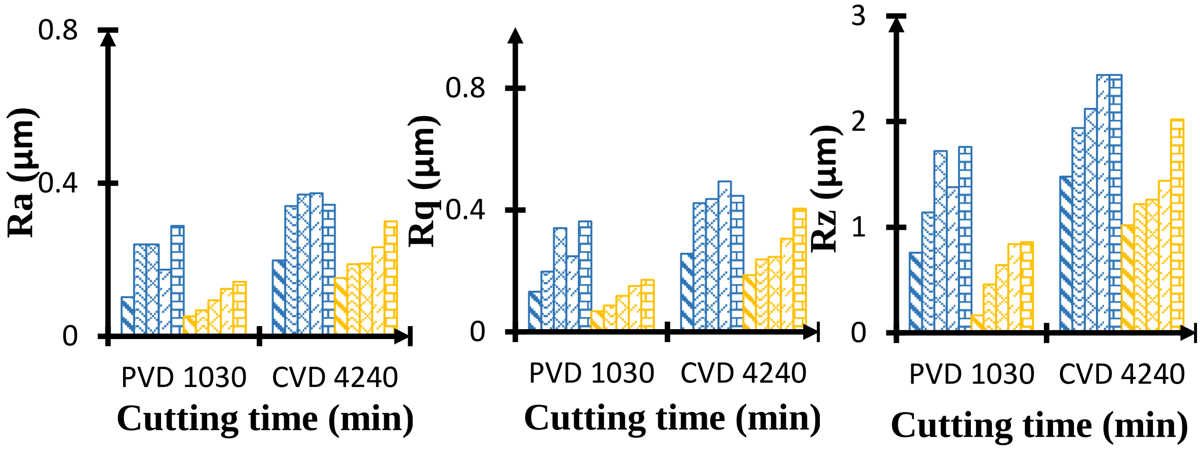
During the experiment, it was noticed that PVD inserts achieved less surface roughness value (Ra, Rq, Rz) at 175 m/min cutting speed in dry condition as compared to the CVD inserts as shown in Fig 4.26 (a) but in MQL condition, CVD 4240 achieved a good surface finish as compared to the PVD inserts at 175 m/min cutting speed. Figure 4.26 (b) shows that in PVD insert, Ra and Rq value were dropped after some time to increase of cutting time, but in CVD inserts, surface roughness increases continuously, whereas less Rq value is achieved in CVD inserts as compared to the PVD inserts. PVD inserts provide good Ra and Rz value at 225 m/min cutting speed as compared to the CVD tool, but less Rq value is achieved in CVD inserts as compared to the PVD inserts at same cutting speed as shown in Fig 4.26 (c). The result shows that PVD inserts provide a good surface finish at high cutting speed whereas CVD inserts is suitable for low cutting speed. PVD inserts have thin coating which achieves good result at high cutting speed whereas CVD inserts has thick, which is suitable for low cutting speed.



(a)



(b)



(c)

Figure 4.26: Surface roughness (Ra, Rq, Rz) result of the inserts after 22.5 min under fixed condition (f=12 mm/min, doc= 1 mm) at cutting speed (a) 175 m/min (b) 200 m/min (C) 225 m/min.

4.4.8 Effects of Cutting Parameters and Lubrication on surface roughness

In this study, the cutting speed varying at fixed depth of cut and feed rate. The effect of varying cutting speed in the surface roughness under milling operation has been observed during different PVD and CVD inserts under different cutting condition as dry and MQL condition. During experiment, it was noticed that MQL machining generates better surface finish when compared to the dry condition. PVD inserts achieved good surface finish due to the thin coating whereas CVD inserts has thick coating, so it generate rough surface during cutting operation. Surface finish increases as the cutting speed increases in MQL condition but in dry condition rough surface is achieved. MQL machining provide good efficiency under high cutting speed in both CVD and PVD inserts.

Table 4.3: Surface roughness results under varying cutting speed at fixed depth of cut and feed rate (f=12mm/min, doc=1mm)

	Ra		Rz		Rq	
	DRY	MQL	DRY	MQL	DRY	MQL
PVD 1030 V = 175 m/min	0.238	0.082	1.5	0.66	0.29	0.106
	0.28	0.206	1.48	1.28	0.294	0.2
	0.388	0.324	2.23	2.00	0.426	0.35
	-	-	-	-	-	-
	-	-	-	-	-	-
PVD 1030 V = 200 m/min	0.326	0.06	0.476	0.102	0.452	0.208
	0.396	0.082	2.1	0.46	0.496	0.326
	0.382	0.174	2.4	1.2	0.472	0.378
	0.538	0.3	2.1	1.6	0.68	0.49
	0.374	0.27	3.48	1.96	2.38	0.62
PVD 1030 V = 225 m/min	0.102	0.052	0.76	0.166	0.132	0.068
	0.144	0.068	1.14	0.46	0.198	0.086
	0.24	0.094	1.72	064	0.34	0.118
	0.174	0.124	1.38	0.84	0.248	0.15
	0.288	0.142	1.76	0.86	0.362	0.178
PVD 1025 V = 150 m/min	0.288	0.088	2.02	0.95	0.372	0.288
	0.32	0.23	2.08	1.36	0.406	0.302
	0.404	0.232	2.2	1.36	0.492	0.374
	0.422	0.25	2.36	1.64	0.5	0.374

	0.448	0.3	2.38	1.86	0.542	0.45
PVD 1025 V = 175 m/min	0.158	0.056	0.5521	0.216	0.21	0.07
	0.2	0.15	1.02	0.44	0.85	0.232
	0.25	0.195	1.2	0.75	1.0	0.254
	0.268	0.202	1.6	0.822	1.32	0.34
	0.388	0.176	1.42	0.8	2.42	1.0
PVD 1025 V = 200 m/min	0.25	0.178	1.24	0.92	0.228	0.166
	0.3	0.24	1.88	1.46	0.368	0.288
	0.39	0.314	2.24	1.78	0.47	0.384
	0.35	0.234	2.16	1.54	0.45	0.296
	0.384	0.196	2.38	1.36	0.474	0.254
CVD 4240 V = 175 m/min	0.148	0.07	1.12	0.58	0.188	0.092
	0.16	0.078	1.12	0.72	0.204	0.124
	0.154	0.096	1.04	1.12	0.192	0.098
	0.366	0.15	2.14	0.6	0.438	0.188
	0.448	0.134	2.5	0.88	0.54	0.166
CVD 4240 V = 200 m/min	0.194	0.11	1.26	0.56	0.238	0.12
	0.346	0.102	2.02	0.74	0.434	0.136
	0.406	0.122	2.56	0.9	0.574	0.168
	0.446	0.258	2.7	1.52	0.612	0.316
	0.458	0.3	2.38	1.82	0.564	0.422
CVD 4240 V = 225 m/min	0.198	0.152	1.48	1.02	0.256	0.186
	0.34	0.188	1.94	1.22	0.422	0.238
	0.37	0.19	2.12	1.26	0.436	0.246
	0.374	0.232	2.44	1.44	0.494	0.306
	0.344	0.3	2.44	2.02	0.446	0.404
CVD 4230	0.864	0.11	1.7	0.98	0.352	0.144
	0.498	0.24	2.92	1.72	0.622	0.342

V = 200 m/min	0.268	0.168	1.92	1.28	0.388	0.242
	0.162	0.136	1.22	1.1	0.21	0.194
	0.170	0.158	1.12	1.06	0.232	0.228
CVD 4230 V = 225 m/min	0.082	0.04	0.7	0.25	0.108	0.075
	0.156	0.082	1.2	0.58	0.216	0.098
	0.186	0.126	1.32	1.08	0.234	0.166
	0.226	0.142	1.58	1.04	0.3	0..178
	0.284	0.204	1.94	1.46	0.374	0.264
CVD 4230 V = 250 m/min	0.262	0.128	1.78	0.88	0.332	0.164
	0.498	0.246	3.48	1.4	0.662	0.3
	1.524	0.28	8.64	1.54	1.876	0.348
	-	-	-	-	-	-
	-	-	-	-	-	-

4.5 Tool Performance during high speed and high depth of cut (cutting speed of 200 m/min, feed rate of 12 mm/min, depth of cut of 3 mm)

4.5.1 Measure Cutting force

In this stage, the experiments was performed in a three repeated passes of 3 mm depth of cut in every work piece for analysis the maximum radial forces which are acted on the work piece during the cutting. The experiments were conducted in MQL (minimum quantity lubrication) and dry lubrication and compare the performance of the PVD and CVD insert in these two machining conditions as shown in Table 4.4. The results shows that in PVD coated inserts, less radial forces are generated as compared to the CVD inserts due to the thin coating as shown in Fig. 4.27. The examinations were first done with the two PVD inserts and measures the max radial forces. Similar operation was done with the two CVD inserts. In this study, cutting length of the workpiece is 55 mm and measure the max radial forces in interval of every 4.5 min till 13.5 min or when catastrophic failure occur. PVD 1025 (TiCN+TiN) coated insert get experience the catastrophic failure in dry machining after 9 min machining due to the thin coating (2-3 micron) which is yet tougher and normally smoother whereas CVD coating are thick (9-20 micron) and highly wear resistant. In MQL machining, radial forces generated are less as compared to the dry machining as shown in Fig. 4.27. PVD tool A (1030) provides good result among all the carbide inserts.

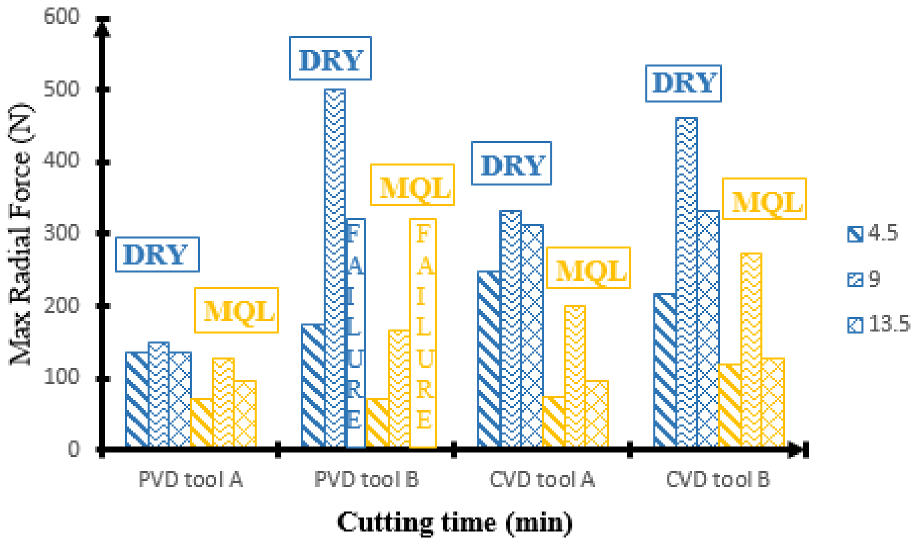


Figure 4.27: Cutting force result of the inserts after 13.5 min under fixed conditions (Vc=200 m/min, f=12 mm/min, doc=3mm).

Table 4.4: Cutting Force of different PVD and CVD inserts under different cutting conditions at feed rate is 12mm/min, depth of cut is 3mm and cutting speed is 200 m/min.

PVD tool A		PVD tool B		CVD tool A		CVD tool B	
DRY	MQL	DRY	MQL	DRY	MQL	DRY	MQL
135.822	69.7808	174.171	71.7215	248.1622	73.0932	217.79	119.8439
148.20	127.311	499.98	166.80	333.017	199.2848	461.1073	274.394
136.802	95.8301	-	-	311.37	95.83014	331.93	127.5696

4.5.2 Measure Tool Wear

Tool wear was measured on different CVD and PVD inserts at constant feed rate of 12mm/min, depth of cut of 3 mm, and cutting speed of 200 m/min. The experiment was performed in three repetition pass. Tool wear was measured in an interval of every 4.5 min till 13.5 min of machining, after every cut of 55 mm check the performance of two PVD and two CVD coated inert. All reading of the tool wear were collected and compared for the performance of these different CVD and PVD coated insert with the different machining (Dry and MQL) condition as shown in Fig. 4.28. PVD tool experience less tool wear during the machining. In CVD inserts, no breakage and failure occur during the machining because it has thick coating and highly wear resistant whereas in PVD inserts, it experience the breakage or catastrophic failure during operation because it has thin coating which help to reduce the tool wear but unfortunately it breaks as PVD tool A experience the catastrophic failure after 9 min machining. CVD tool A provide the best results as compared to the CVD tool B. PVD tools B gives good result as compared to the PVD tool A and PVD tool B gives the best result among all the PVD and CVD inserts.

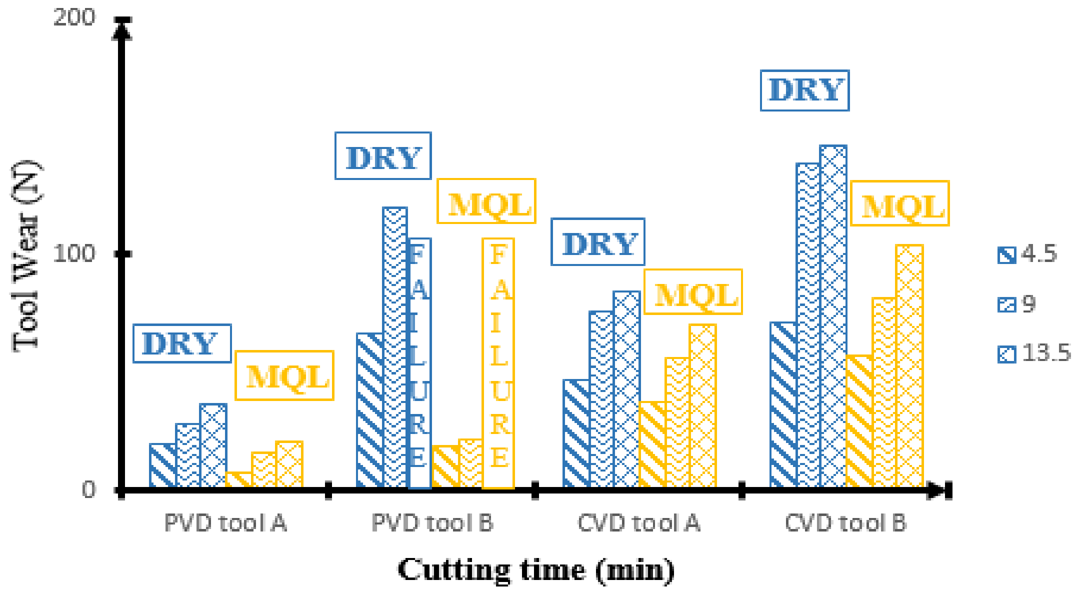


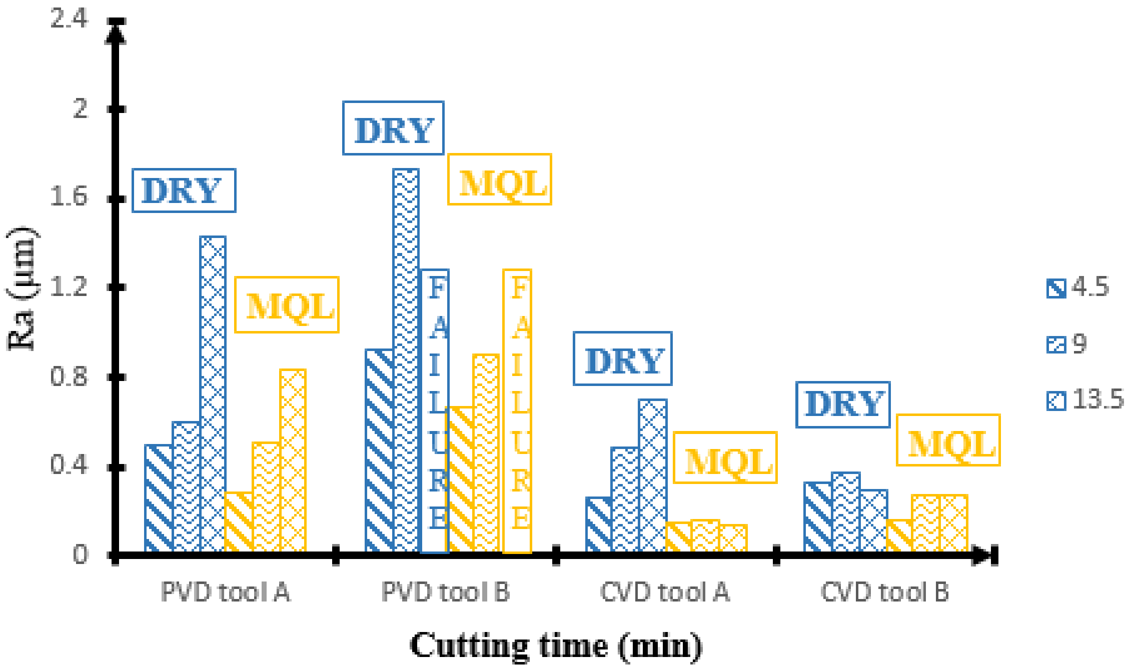
Figure 4.28: Tool wear result of the inserts after 13.5 min under fixed conditions (Vc=200 m/min, f=12 mm/min, doc=3mm).

Table 4.5: Tool Wear results under fixed cutting speed, depth of cut and feed rate (Vc = 200m/min, f = 12mm/min, doc = 3mm)

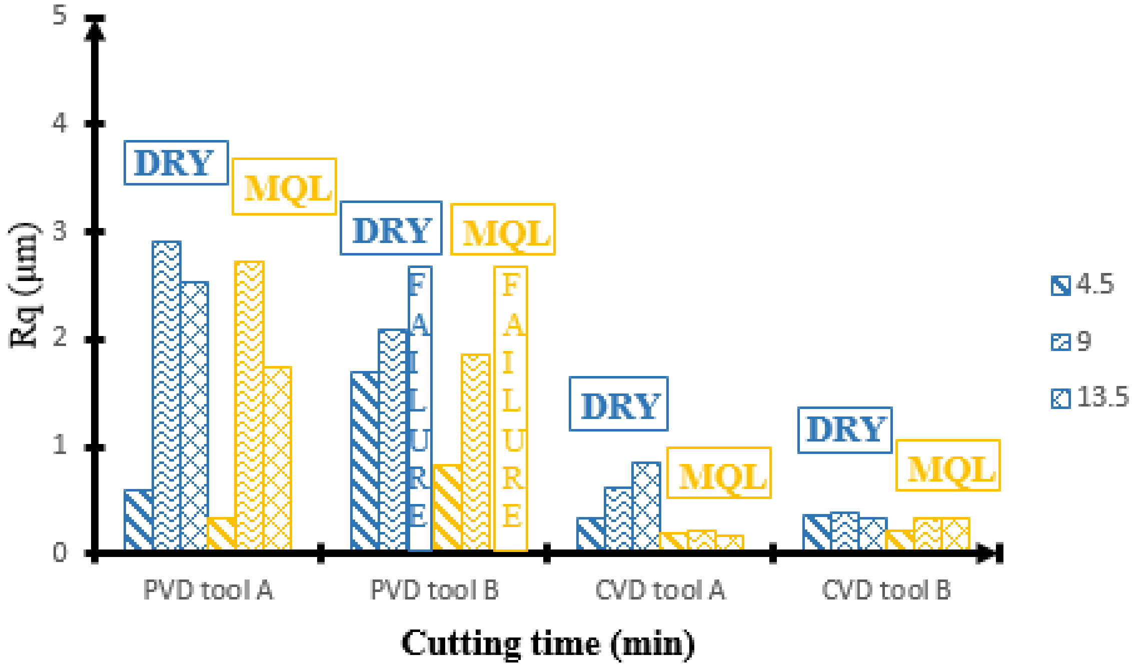
PVD_1025		PVD_1030		CVD_4230		CVD_4240	
DRY	MQL	DRY	MQL	DRY	MQL	DRY	MQL
66.6	18.7	20.3	7.3	46.6	38	71.8	57.7
119.7	22.1	28.1	16.1	76.1	56.2	138.5	81.7
-	-	36.4	21.0	84.2	70.7	146.3	104.6

4.5.3 Measure surface roughness

At this stage, surface roughness are measured on two different PVD and CVD coated inserts under fixed cutting parameter for, speed of 200 m/min, depth of cut of 3 mm and feed rate of 12 mm/min. The experiment was performed in three repetition pass of every insert to know the performance of the tool after every 4.5 min. The same process is continuing till 13.5 min and reading is noted by every 4.5 min interval of the cutting. Experiments performed on the different inserts and all the readings were collected for surface roughness of Ra, Rq, Rz and it was concluded that in MQL machining has good surface finish as compared to the dry machining as shown in Fig. 4.29. And among all four different coated carbide inserts CVD tool provides a good surface finish as compared to the PVD tool because it has a thick layer coating which has an ability to wear resistance and also effective in a high heat condition. CVD tool A has a large nose radius which offer outstanding and increase the resistance of the built-up-edge and ability to work on the gummy material. CVD tool A provides a good surface finish in dry condition and CVD tool B provides a good surface finish in MQL condition. PVD tool A provide a good surface finish in MQL condition as compared to the PVD tool B because PVD tool A has TiAlN coating which is stable as well as more harder and also more effective in high temperature than TiCN coating which is in PVD tool B.



(a)



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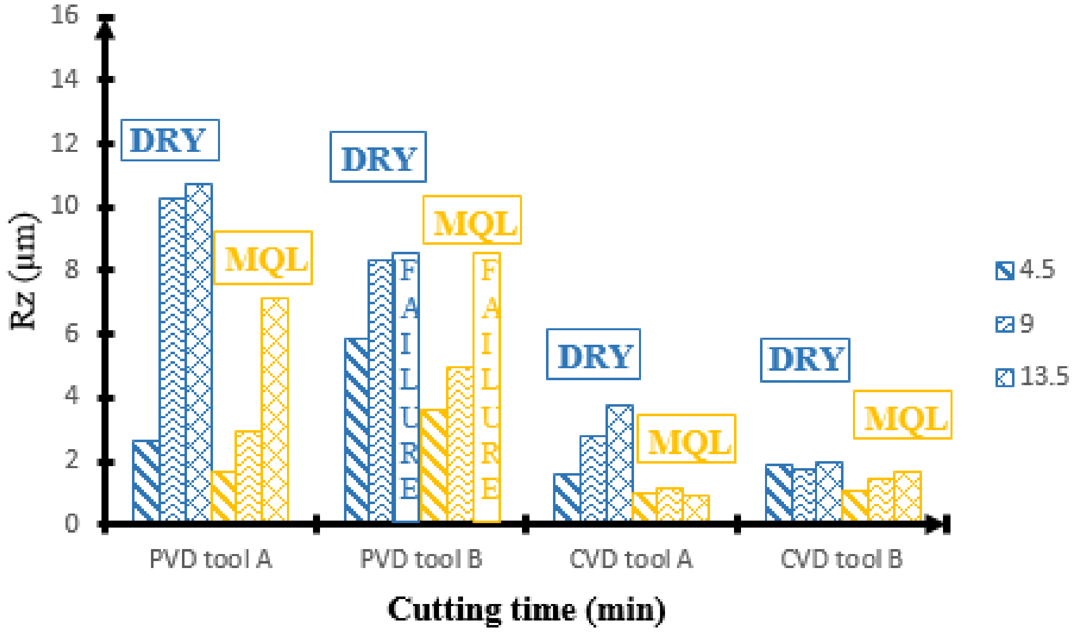

(c)

Figure 4.29: Surface roughness value of the inserts after 13.5 min under fixed conditions (Vc = 200 m/min, f = 12 mm/min, doc = 3mm) (a) Ra value (b) Rq value (c) Rz value

Table 4.6: Surface roughness results under fixed cutting speed, depth of cut and feed rate (Vc = 200 m/min, f =12 mm/min, doc = 3 mm)

	Ra		Rz		Rq	
	DRY	MQL	DRY	MQL	DRY	MQL
PVD tool A V = 200 m/sec	0.495	0.28	2.675	1.678	0.6	0.335
	0.5925	0.5126	10.3	2.925	2.9	2.72
	1.4325	0.8356	10.7	7.125	2.5325	1.7325
PVD tool B V = 200 m/sec	0.92	0.66	5.84	3.6	1.68	0.82
	1.732	0.9	8.34	4.96	2.098	1.86-
	-	-	-	-	-	-
CVD tool A V = 200 m/sec	0.2625	0.1475	1.6	1.025	0.3225	0.1875
	0.488	0.1625	2.76	1.125	0.608	0.22
	0.7	0.1325	3.725	0.885	0.8525	0.165
CVD tool B V = 200 m/sec	0.332	0.165	1.88	1.08	0.3565	0.204
	0.3725	0.275	1.75	1.475	0.3725	0.33
	0.29	0.27	1.984	1.7	0.3775	0.335

4.6 Summary and Discussion

There are the two factors such as speed and depth of cut, which affects the cutting operation during machining. This study observes that when cutting operation was performed at fixed speed, i.e. cutting speed 200 m/min, feed rate 12 mm/min and depth of cut 3 mm. PVD 1025, experience the catastrophic failure after 9 min of cutting time. During cutting it was observed that CVD generates very high cutting force as compared to the PVD tool. The result was compared with the same cutting condition except the depth of cut i.e. depth of cut 1 mm and 3 mm. It was noticed that PVD 1030, PVD 1025 and CVD tool A experience high cutting force during cutting operation at high depth of cut as compared to the depth of cut 1 mm but CVD tool B experience low cutting force during the high depth of cut as compared to the lowest depth of cut. Hence, CVD tool B was suitable for machining under high depth of cut. Cutting speed also affects the output parameter such as cutting force, surface roughness, and tool wear. As the cutting speed increases, the cutting ability of the tool also increase in MQL condition as compared with the dry condition. But PVD tool B provides the good result in both conditions under the low cutting speed, i.e. cutting speed 150 m/min so it mainly used for the light cut.

CHAPTER 5

CONCLUSION AND SCOPE FOR FUTURE WORK

5.1 Introduction

This chapter gives a brief sketch about the result of this research, which performed on different PVD and CVD coated inserts to know the effect of cutting speed under dry and MQL condition during end milling of EN-31. This study focused on the advantages of MQL machining over dry machining condition. In this experiment, trials are performed to observe the effect of varying cutting speed on the cutting forces, surface roughness and tool wear. Key results of the experiment are as follows:

5.2 Conclusions

In this investigation, the results of dry and MQL machining of EN-31 hardened die steel are compared in terms of cutting force, surface roughness and tool wear. All milling experiments are conducted for a cutting length of 55 mm and experiments stop either on reaching its complete machining time or tool experience the catastrophic failure as occur on PVD 1030 in cutting speed 175 m/min and CVD 4230 experience it at cutting speed 250 m/min under fixed depth of cut 1 mm, feed rate = 12 mm/min. Whereas PVD 1025 feel catastrophic failure at cutting speed 200 m/min, feed rate 12 mm/min and depth of cut 3 mm. The following conclusions can be drawn on the basis of this experiment.

- In MQL cutting, less cutting force, better surface finish and less tool wear are achieving as compared to the dry cutting.
- MQL machining helps to reduce the tool wear which leads to increase the tool life of the insert. CVD 4240 provides less tool wear at 225 m/min cutting speed under MQL condition, whereas in dry condition, less tool wear is achieved at 200 m/min
- MQL condition, increase the machine capability to work at high cutting speed than dry condition

- PVD 1030 provides a good surface finish as well as decrease tool wear as compare to the PVD 1025 due to the harder and more stable coating and also effective in high temperature as well as abrasion iron at low speed.
- CVD 4230 provides good results as compare to the CVD 4240 in all cutting conditions under dry and MQL condition.
- PVD tool experience the catastrophic failure, whereas CVD tool did continuous machining because CVD tool have thick coating and have ability to work on the gummy material.
- CVD 4230 experience the tool wear more than 415 micrometers at cutting speed 250 m/min in dry condition after third cut.
- PVD coated inserts, less radial forces are generated as compared to the CVD inserts due to the thin coating.
- PVD 1025 (TiCN+TiN) coated insert get experience the catastrophic failure in dry machining after 9 min machining at cutting speed 200 m/min, depth of cut 3 mm and feed rate 12 mm/min whereas PVD 1030 (TiAlN+TiN) experience the catastrophic failure at cutting speed 175 m/min, depth of cut 1 mm and feed rate 12 mm/min after 13.5 min due to the thin coating (2-3 micron) which is yet tougher and normally smoother.

5.3 Future works

In this study, many factors come which needs a further study, but the most significant factor which need special attention to further study is:

- During experiments, it was observed that the nozzle angle plays a significant role in the performance of the surface of the machined part. So further study should be done on the angle of the nozzle.
- The experiment will also perform by a varying federate under fixed doc and speed to measure the feed rate on cutting operation.
- Chip morphology can also investigate in further experiment.
- ANOVA and orthogonal array can be used to analyze the result of this experimental study.
- CFD analysis can also be used to measure the flow of the coolant which deliver from the nozzle.

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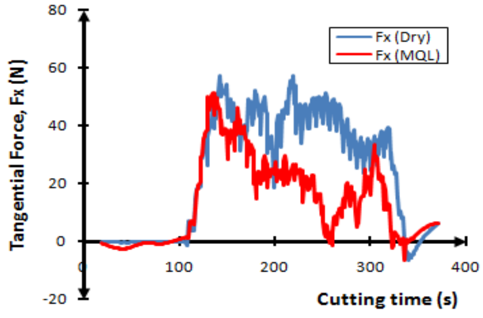
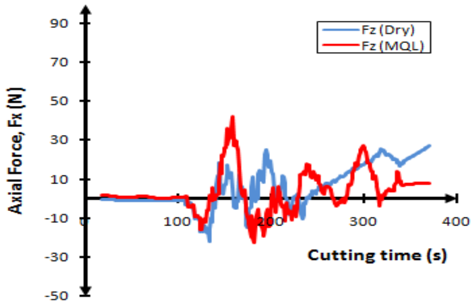
APPENDICE 1

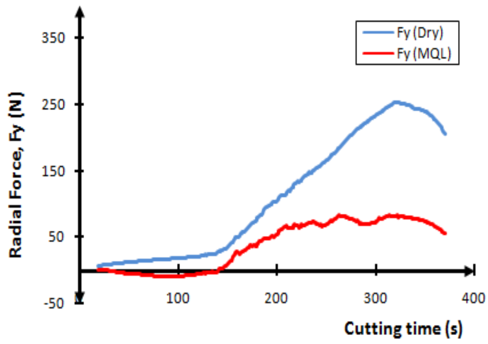
CUTTING FORCE



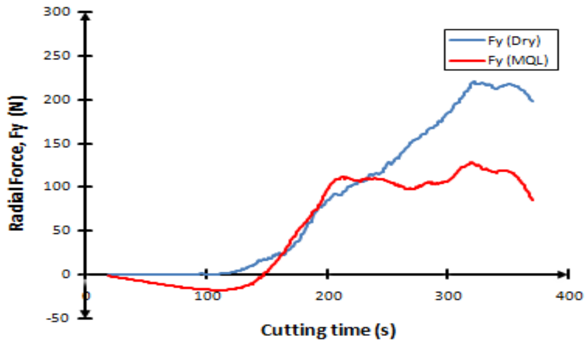
(a): CVD tool A tangential force and cutting time



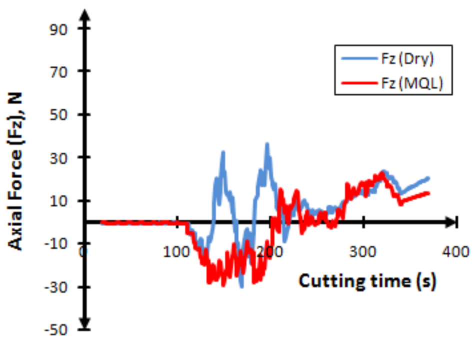
(b): CVD tool A axial force and cutting time



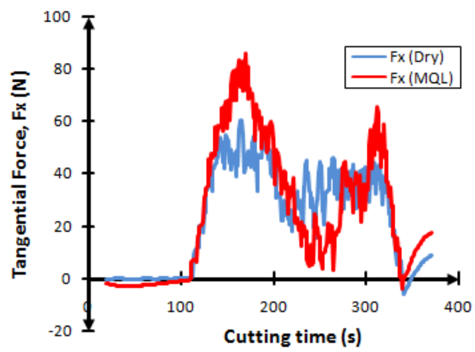
(c): CVD tool A radial force and cutting time



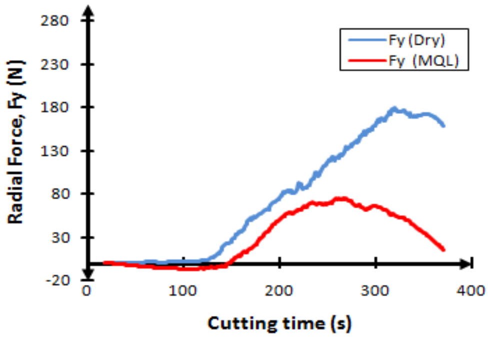
(d): CVD tool B radial force and cutting time



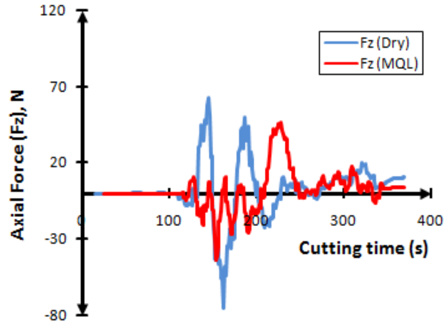
(e): CVD tool B axial force and cutting time



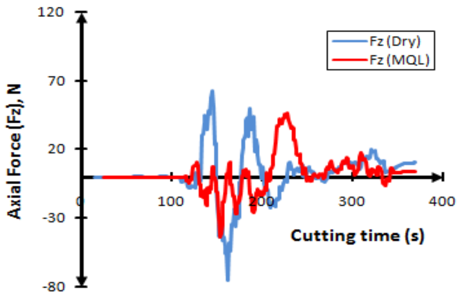
(f): CVD tool B tangential force and cutting time



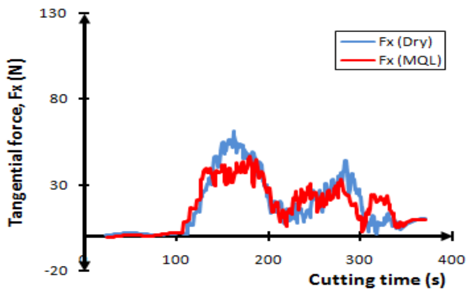
(g): PVD tool A radial force and cutting time



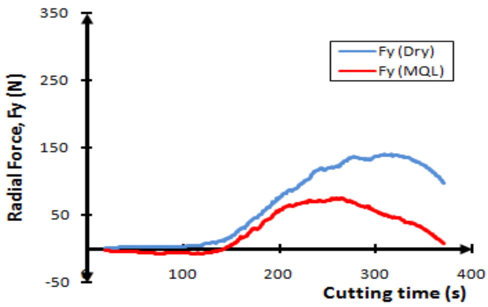
(h): PVD tool A tangential force and cutting time



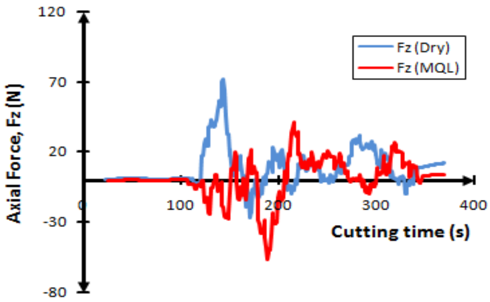
(i): PVD tool A axial force and cutting time



(j): PVD tool B tangential force and cutting time

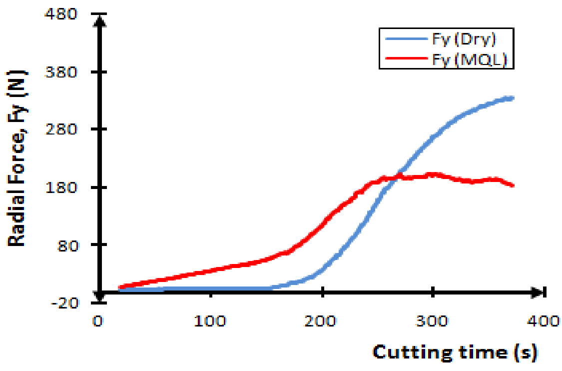


(k): PVD tool B radial force and cutting time

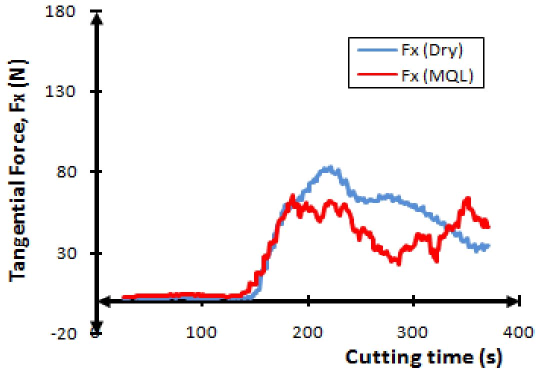


(l): PVD tool B tangential force and cutting time

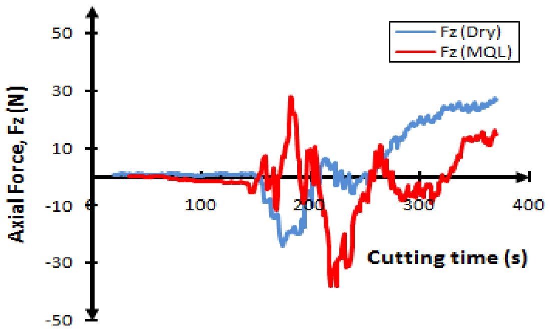
Figure A.1: Comparative graphs of cutting force for CVD and PVD insert in dry and MQL conditions was shown (in graphs a, b, c, d, e, f, g, h, i, j, k and l) after 4.5 min at fixed feed rate of 12 mm/min, depth of cut of 3 mm and cutting speed of 200 m/min.



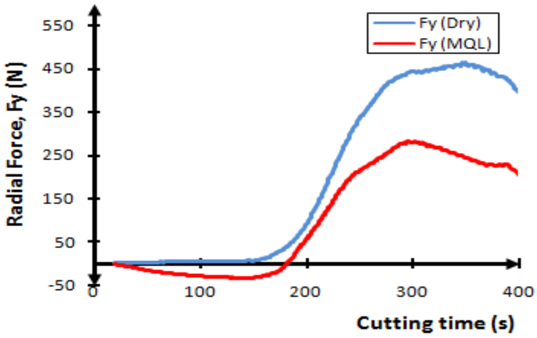
(a): CVD tool A radial force and cutting time



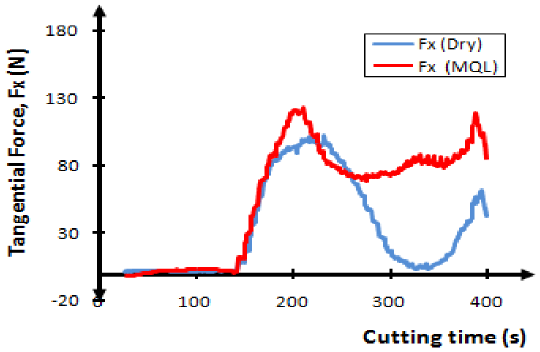
(b): CVD tool A tangential force and cutting time



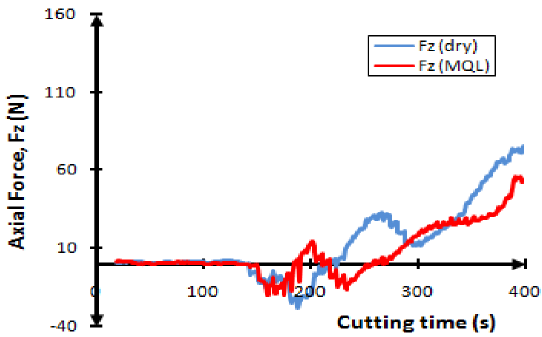
(c): CVD tool A axial force and cutting time



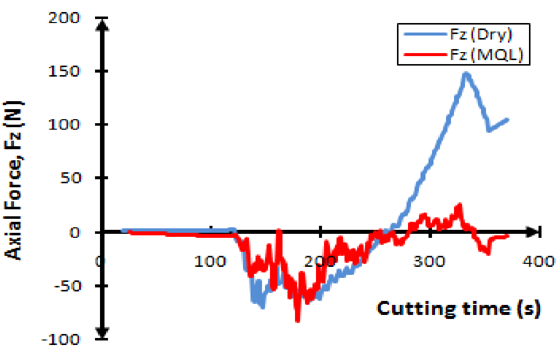
(d): CVD tool B radial force and cutting time



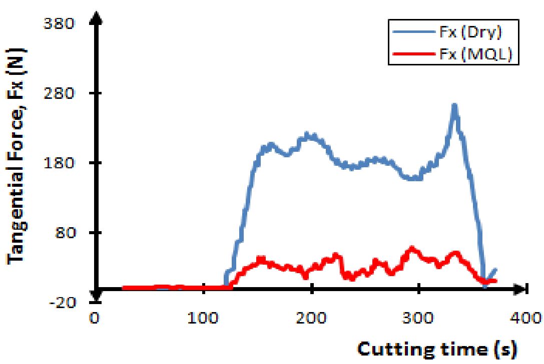
(e): CVD tool B tangential force and cutting time



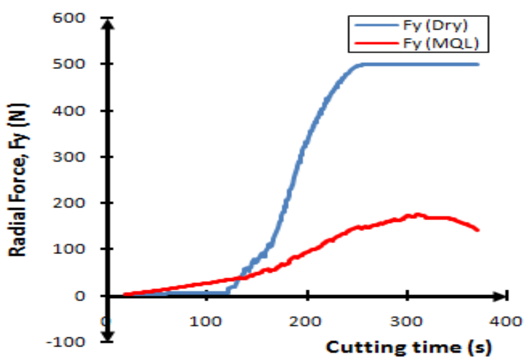
(f): CVD tool B axial force and cutting time



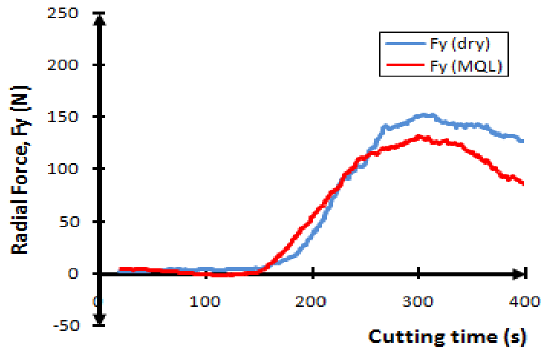
(g): PVD tool A axial force and cutting time



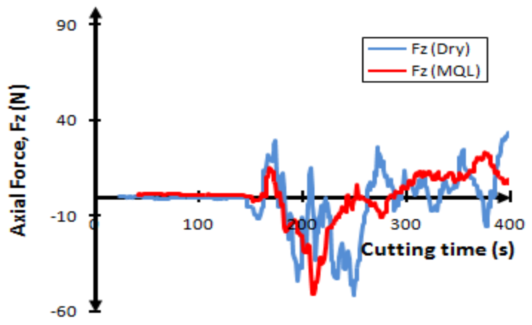
(h):PVD tool A tangential force and cutting time



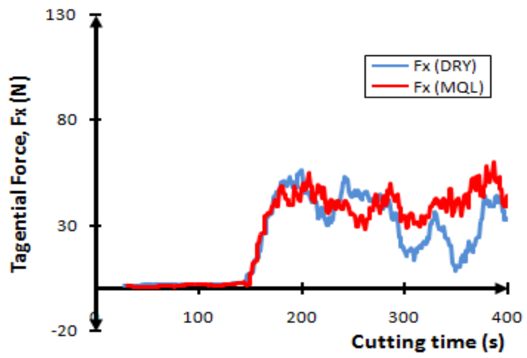
(i): PVD tool A radial force and cutting time



(j): PVD tool B radial force and cutting time

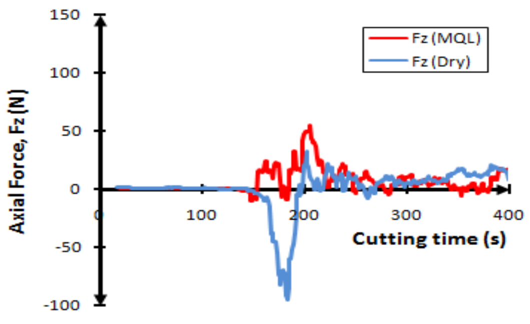


(k): PVD tool B axial force and cutting time

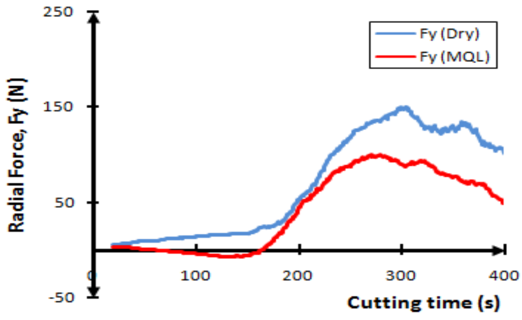


(l): PVD tool B tangential force and cutting time

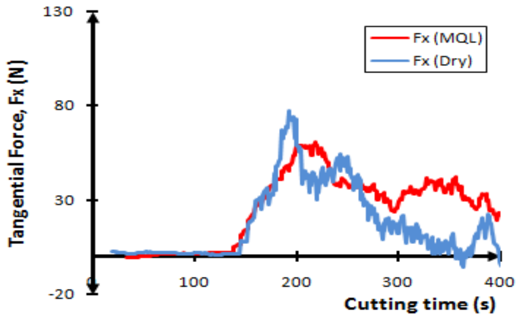
Figure A.2: Comparative graphs of cutting force for CVD and PVD insert in dry and MQL conditions was shown (in graphs a, b, c, d, e, f, g, h, i, j, k and l) after 9 min at fixed feed rate of 12 mm/min, depth of cut of 3 mm and cutting speed of 200 m/min.



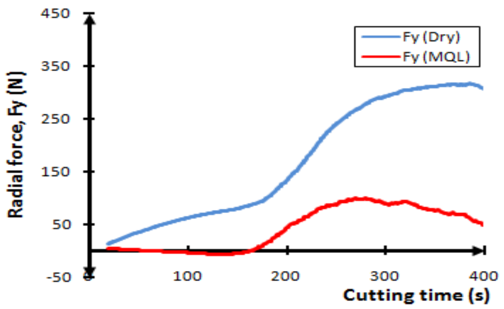
(a): PVD tool B axial force and cutting time



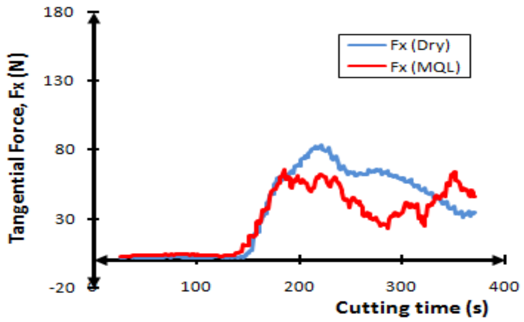
(b): PVD tool B radial force and cutting time



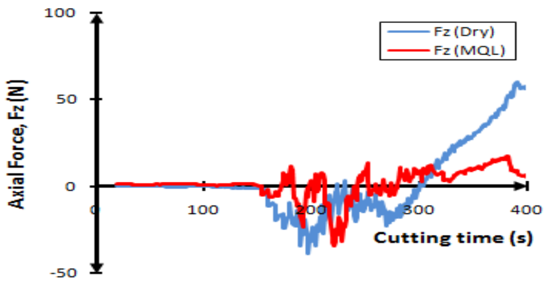
(c): PVD tool B tangential force and cutting time



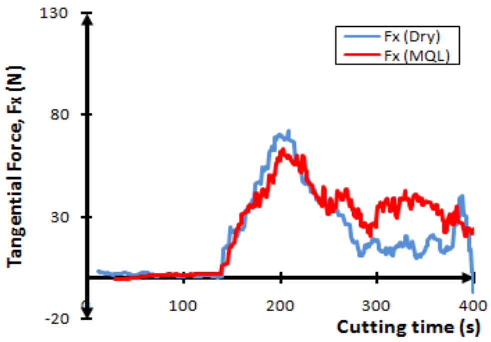
(d): CVD tool A radial force and cutting time



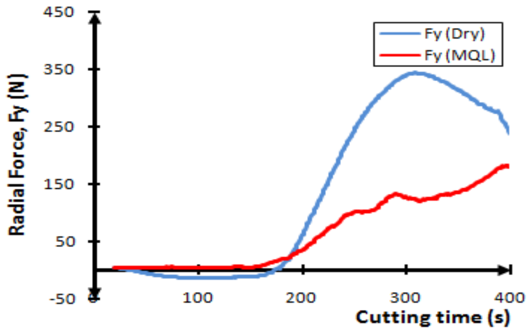
(e): CVD tool A tangential force and cutting time



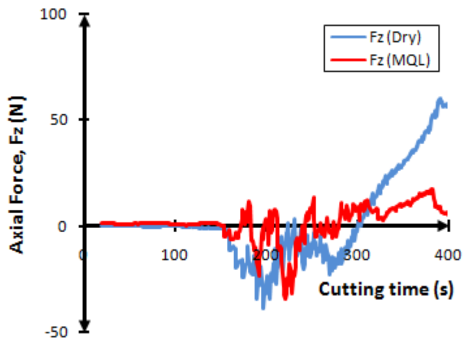
(f): CVD tool A axial force and cutting time



(g): CVD tool B tangential force and cutting time

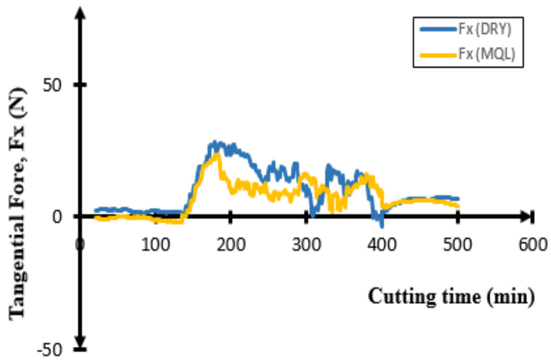


(h): CVD tool B radial force and cutting time

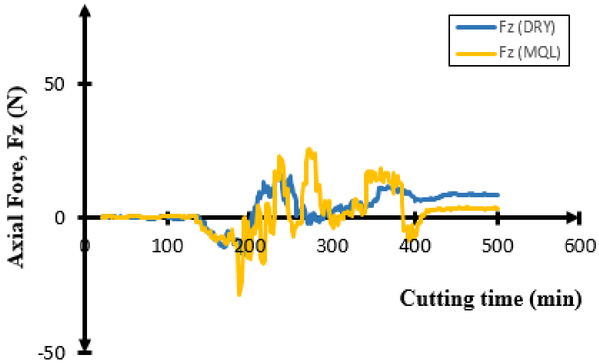


(i): CVD tool B axial force and cutting time

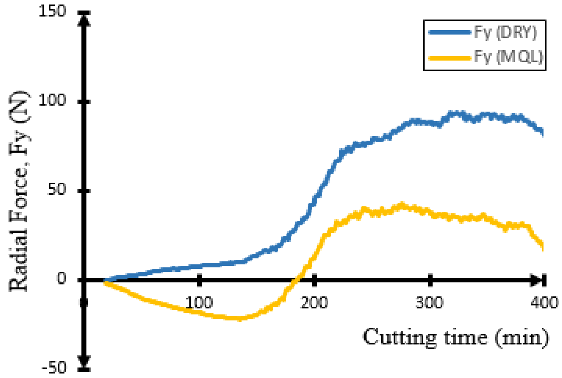
Figure A.3: Comparative graphs of cutting force for CVD and PVD insert in dry and MQL conditions was shown (in graphs a, b, c, d, e, f, g, h, i, j, k and l) after 4.5 min at fixed feed rate of 12 mm/min, depth of cut of 3 mm and cutting speed of 200 m/min.



(a): Tangential force and cutting time

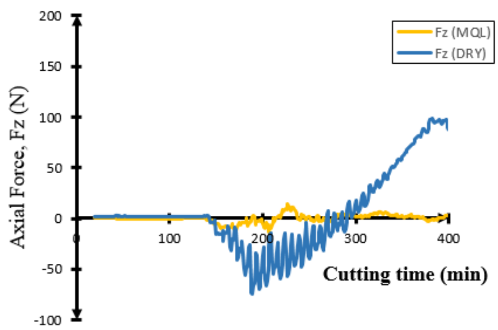


(b): Axial force and cutting time

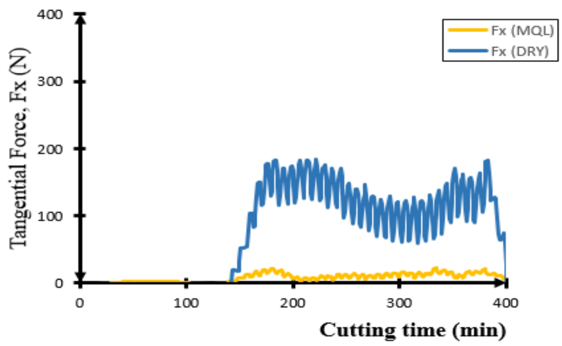


(c): Radial force and cutting time

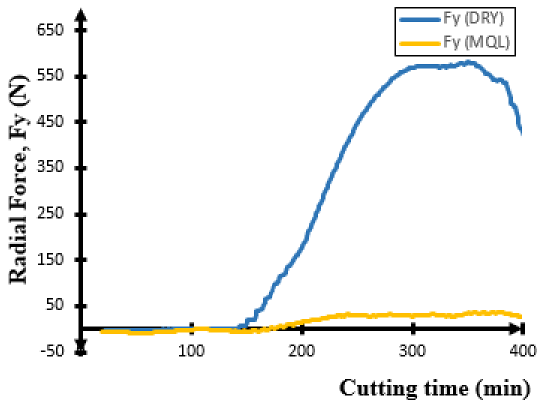
Figure A.4: Comparative graphs of cutting force for PVD 1025 insert in dry and MQL conditions was shown (in graphs a, b and c) after 22.5 min at fixed feed rate of 12 mm/min, depth of cut of 1 mm and cutting speed of 150 m/min.



(a): Axial force and cutting time

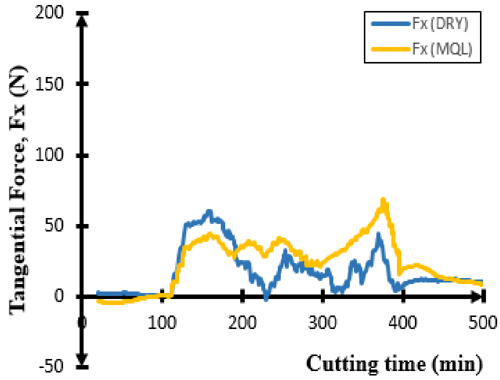


(b): Tangential force and cutting time

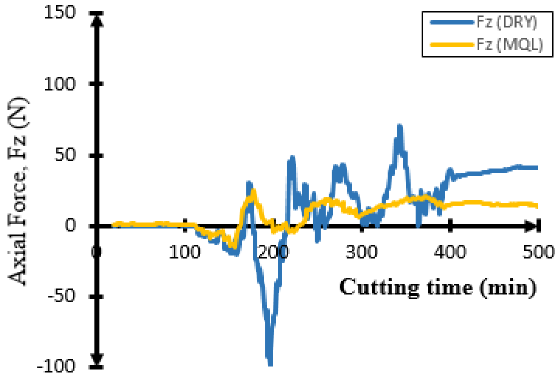


(c): Radial force and cutting time

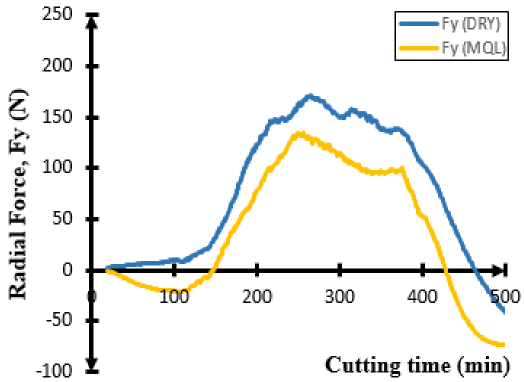
Figure A.5: Comparative graphs of cutting force for PVD 1025 insert in dry and MQL conditions was shown (in graphs a, b and c) after 22.5 min at fixed feed rate of 12 mm/min, depth of cut of 1 mm and cutting speed of 175 m/min.



(a): Tangential force and cutting time

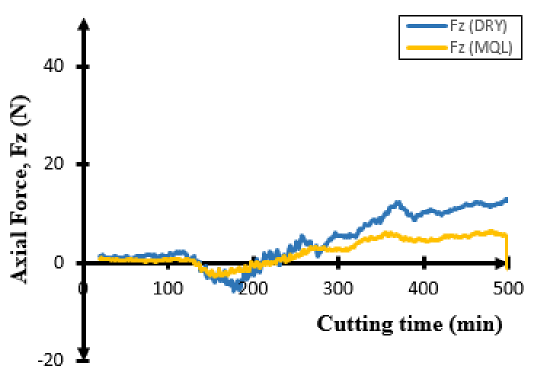


(b): Axial force and cutting time

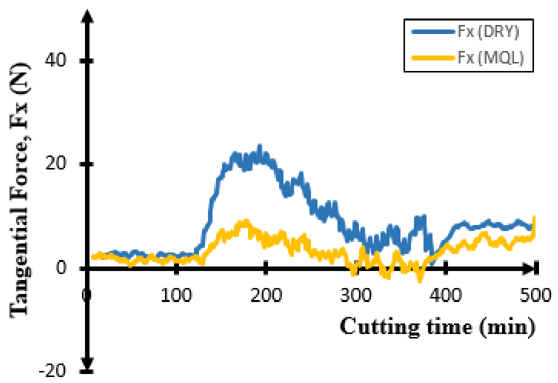


(c): Radial force and cutting time

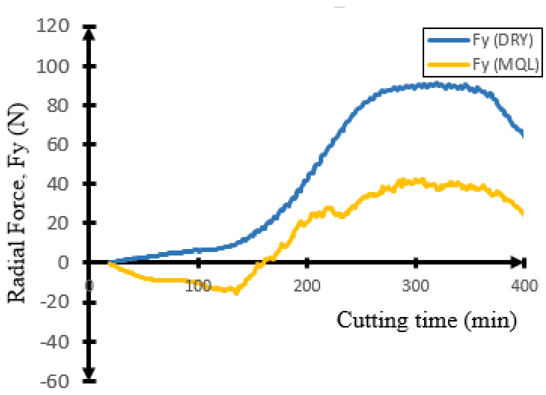
Figure A.6: Comparative graphs of cutting force for PVD 1025 insert in dry and MQL conditions was shown (in graphs a, b and c) after 22.5 min at fixed feed rate of 12 mm/min, depth of cut of 1 mm and cutting speed of 200 m/min.



(a): Axial force and cutting time

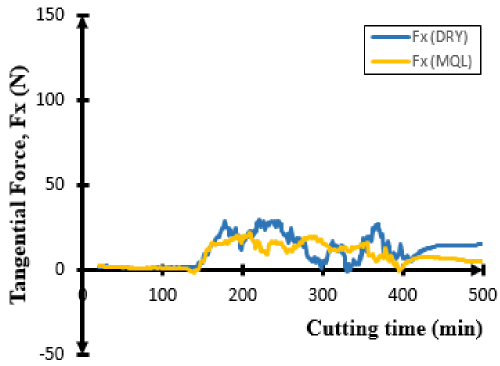


(b): Tangential force and cutting time

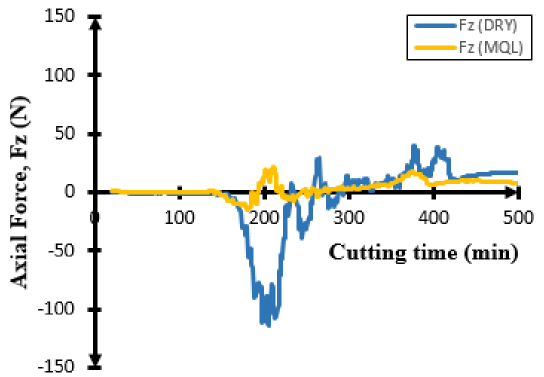


(c): Radial force and cutting time

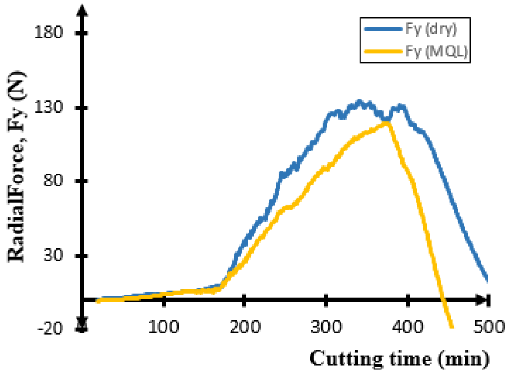
Figure A.7: Comparative graphs of cutting force for PVD 1030 insert in dry and MQL conditions was shown (in graphs a, b and c) after 22.5 min at fixed feed rate of 12 mm/min, depth of cut of 1 mm and cutting speed of 175 m/min.



(a): Tangential force and cutting time

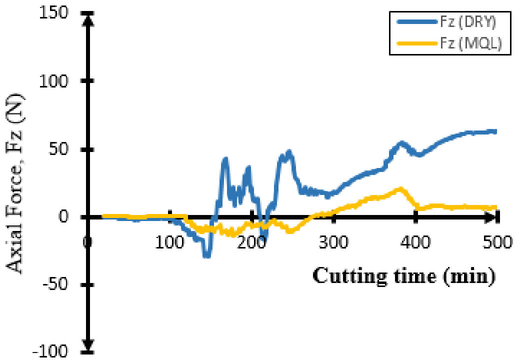


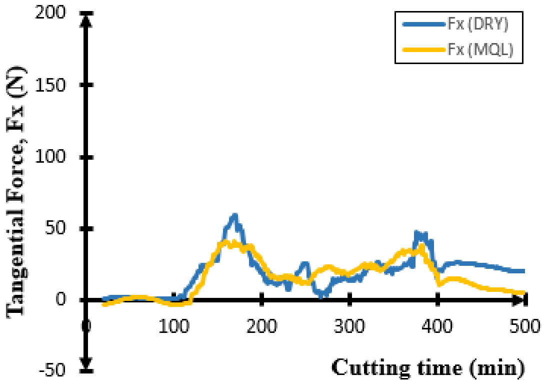
(b): Axial force and cutting time



(c): Radial force and cutting time

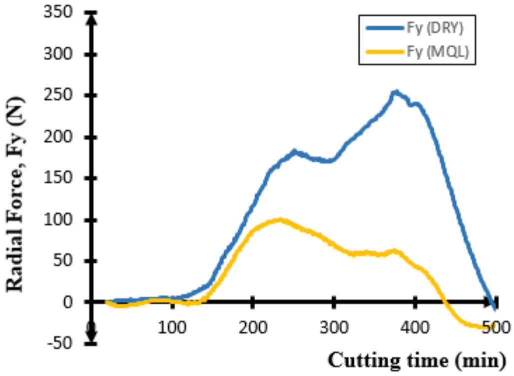
Figure A.8: Comparative graphs of cutting force for PVD 1030 insert in dry and MQL conditions was shown (in graphs a, b and c) after 22.5 min at fixed feed rate of 12 mm/min, depth of cut of 1 mm and cutting speed of 200 m/min.





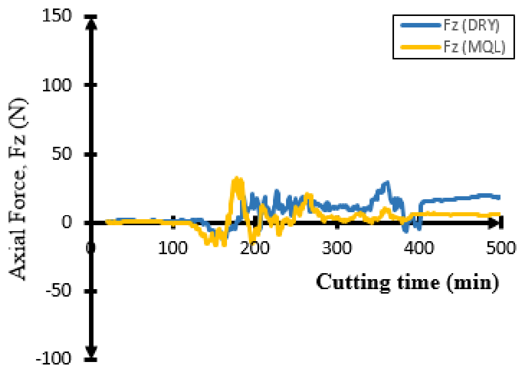
(a): Axial force and cutting time

(b): Tangential force and cutting time

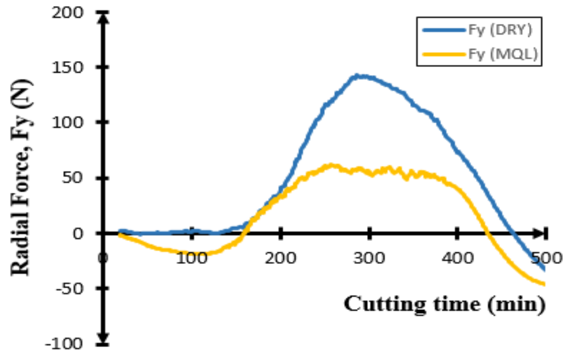


(c): Radial force and cutting time

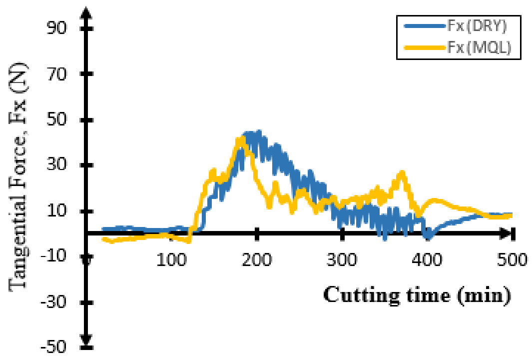
Figure A.9: Comparative graphs of cutting force for PVD 1030 insert in dry and MQL conditions was shown (in graphs a, b and c) after 22.5 min at fixed feed rate of 12 mm/min, depth of cut of 1 mm and cutting speed of 225 m/min.



(a): Axial force and cutting time

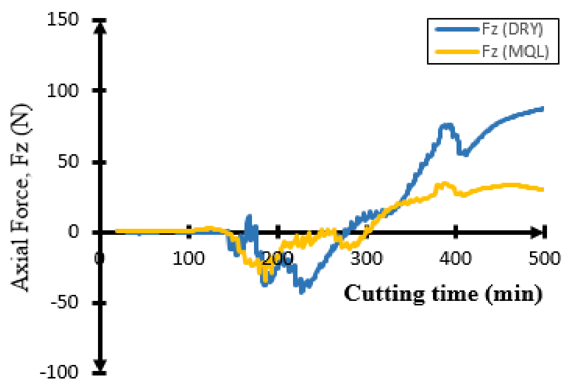


(b): Radial force and cutting time

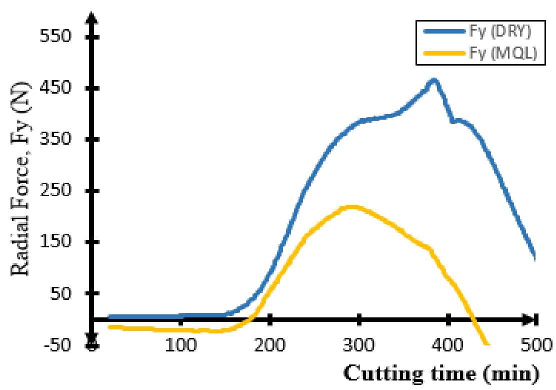


(c): Tangential force and cutting time

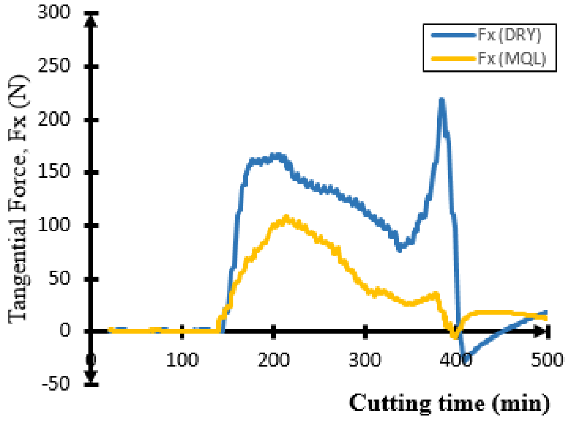
Figure A.10: Comparative graphs of cutting force for CVD 4240 insert in dry and MQL conditions was shown (in graphs a, b and c) after 22.5 min at fixed feed rate of 12 mm/min, depth of cut of 1 mm and cutting speed of 175 m/min.



(a): Axial force and cutting time

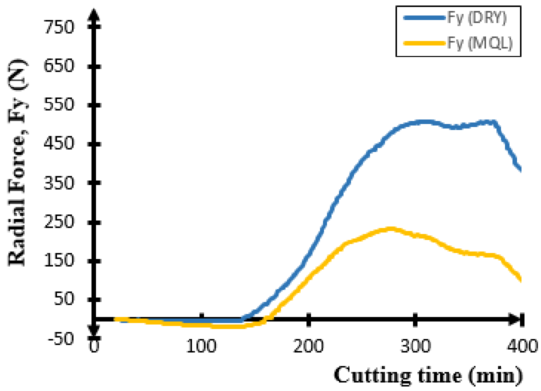


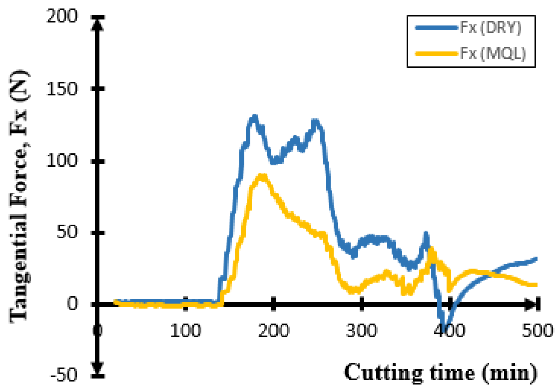
(b): Radial force and cutting time



(c): Tangential force and cutting time

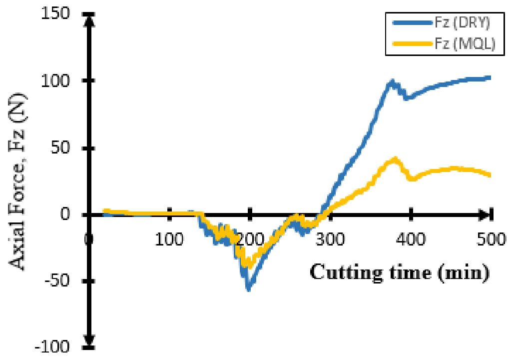
Figure A.11: Comparative graphs of cutting force for CVD 4240 insert in dry and MQL conditions was shown (in graphs a, b and c) after 22.5 min at fixed feed rate of 12 mm/min, depth of cut of 1 mm and cutting speed of 200 m/min.





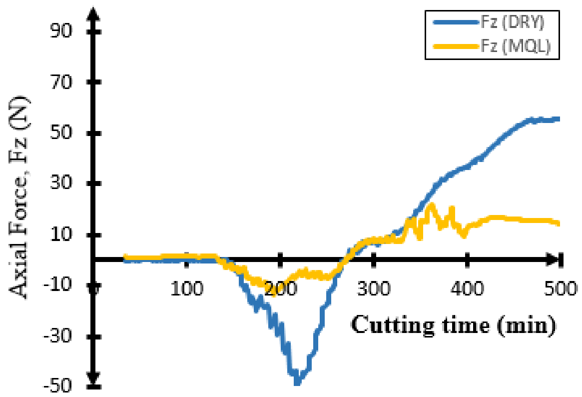
(a): Radial force and cutting time

(b): Tangential force and cutting time

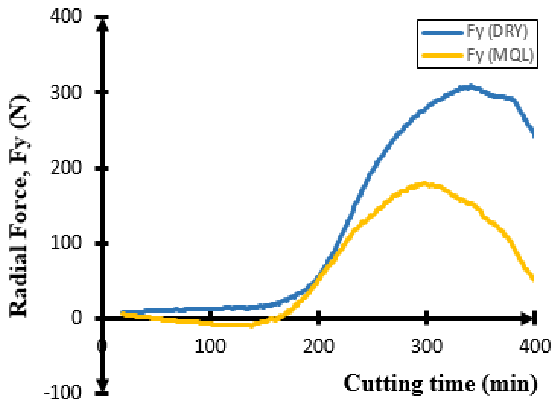


(c): Axial force and cutting time

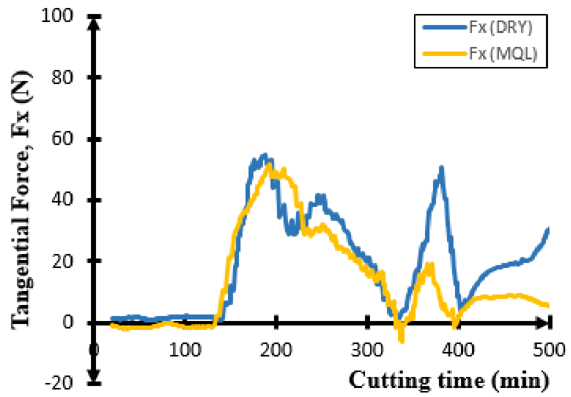
Figure A.12: Comparative graphs of cutting force for CVD insert in dry and MQL conditions was shown (in graphs a, b and c) after 22.5 min at fixed feed rate of 12 mm/min, depth of cut of 1 mm and cutting speed of 225 m/min.



(a): Axial force and cutting time

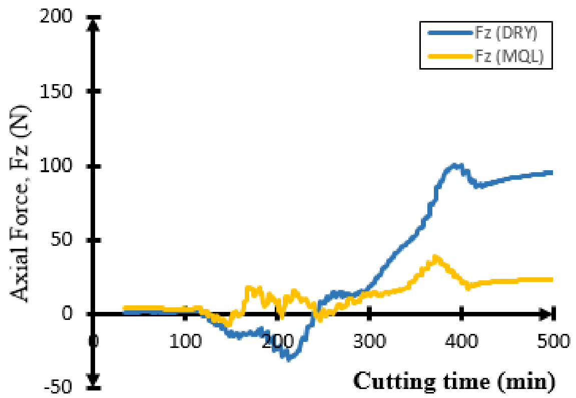


(b): Radial force and cutting time

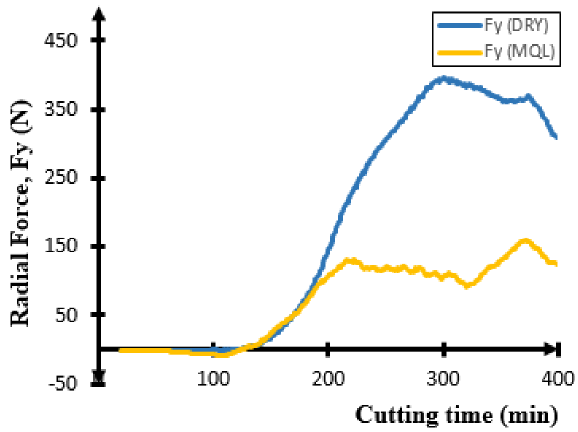


(c): Tangential force and cutting time

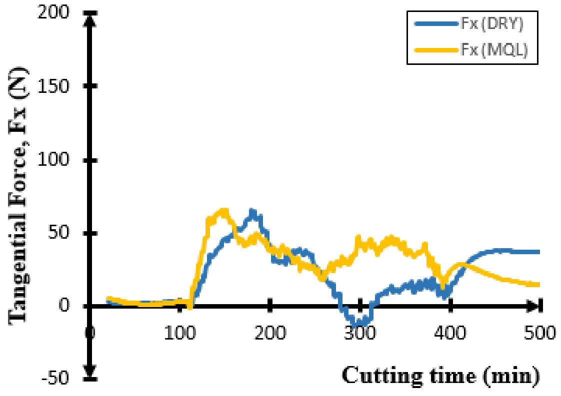
Figure A.13: Comparative graphs of cutting force for CVD 4230 insert in dry and MQL conditions was shown (in graphs a, b and c) after 22.5 min at fixed feed rate of 12 mm/min, depth of cut of 1 mm and cutting speed of 200 m/min.



(a): Axial force and cutting time

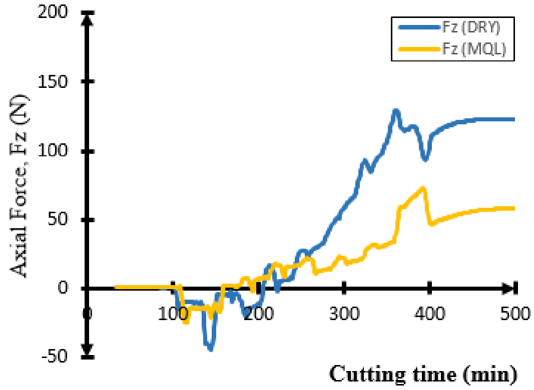


(b): Radial force and cutting time

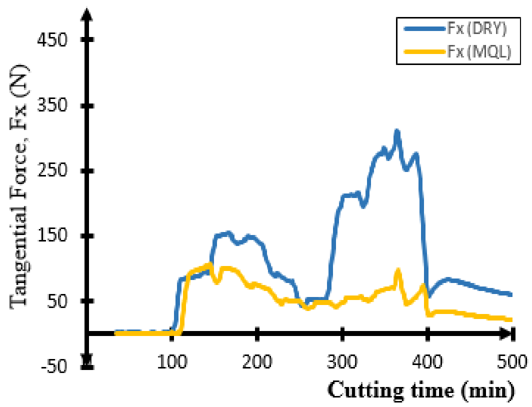


(c): Tangential force and cutting time

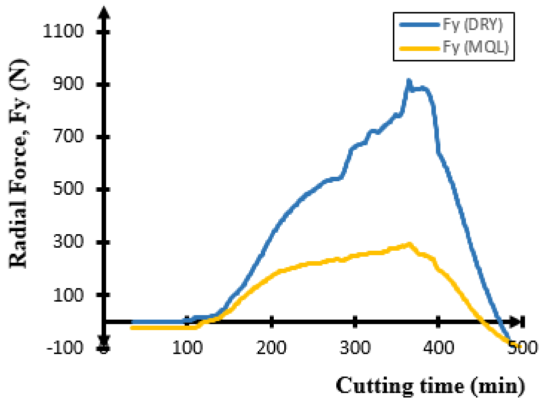
Figure A.14: Comparative graphs of cutting force for CVD 4230 insert in dry and MQL conditions was shown (in graphs a, b and c) after 22.5 min at fixed feed rate of 12 mm/min, depth of cut of 1 mm and cutting speed of 225 m/min.



(a): Axial force and cutting time



(b): Tangential force and cutting time

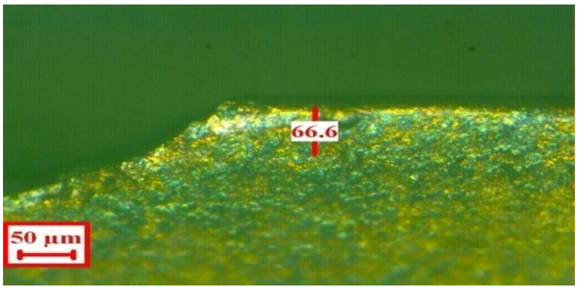


(c): Radial force and cutting time

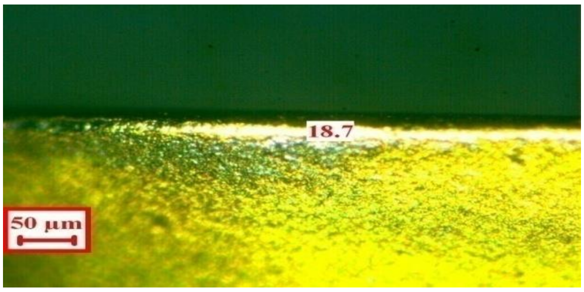
Figure A.15: Comparative graphs of cutting force for CVD 4230 insert in dry and MQL conditions was shown (in graphs a, b and c) after 22.5 min at fixed feed rate of 12 mm/min, depth of cut of 1 mm and cutting speed of 250 m/min.

APPENDICE 2

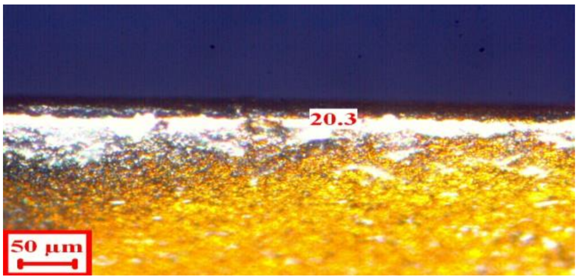
TOOL WEAR



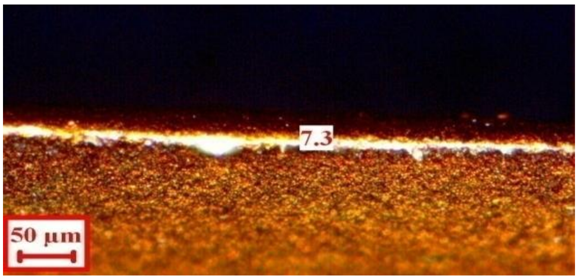
(a): PVD tool A dry condition



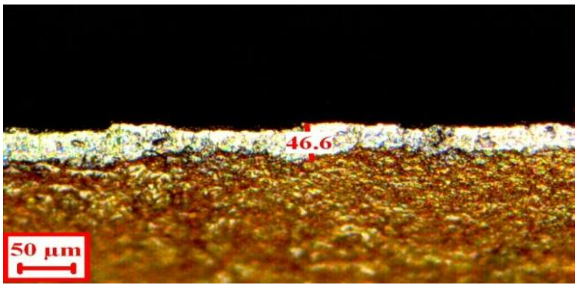
(b): PVD tool A MQL condition



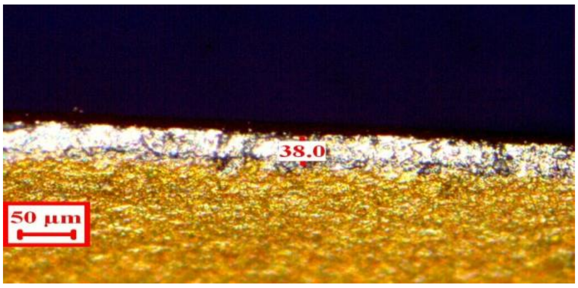
(c): PVD tool B dry condition



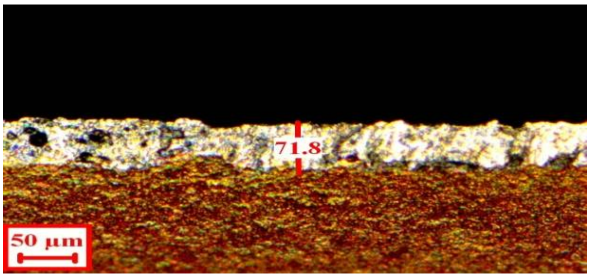
(d): PVD tool B MQL condition



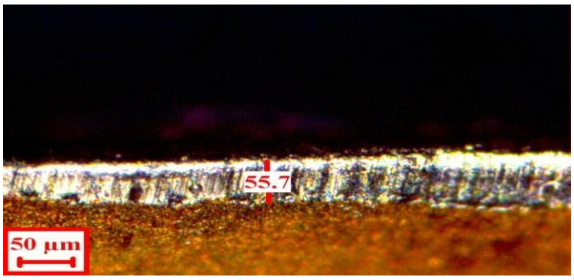
(e): CVD tool A dry condition



(f): CVD tool A MQL condition

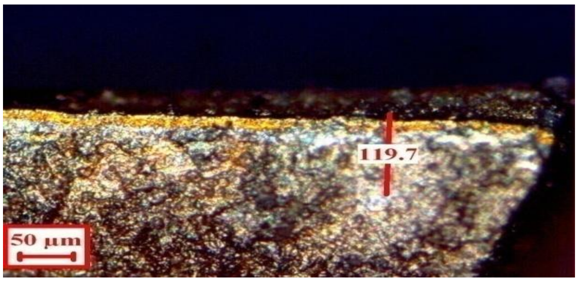


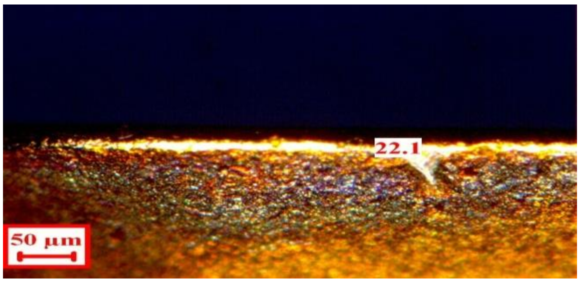
(g): CVD tool B dry condition



(h): CVD tool B MQL condition

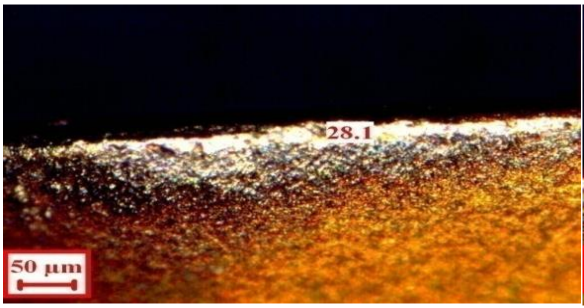
Figure B.1: Microscopy of tool wear for CVD and PVD insert in dry and MQL conditions was shown (in graphs a, b, c, d, e, f, g and h) after 4.5 min at fixed feed rate of 12 mm/min, depth of cut of 3 mm and cutting speed of 200 m/min.

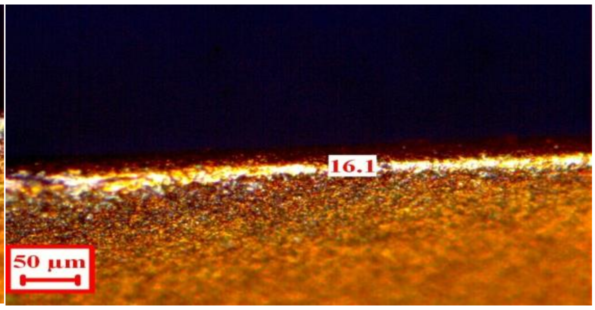




(a): PVD tool A dry condition

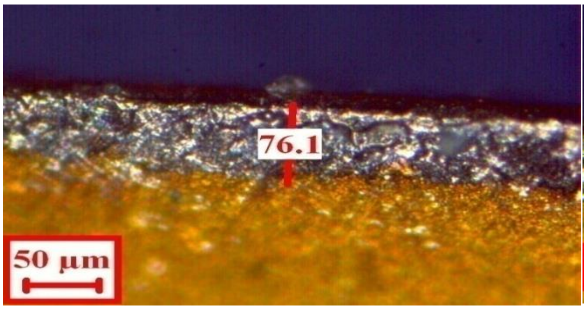
(b): PVD tool MQL condition

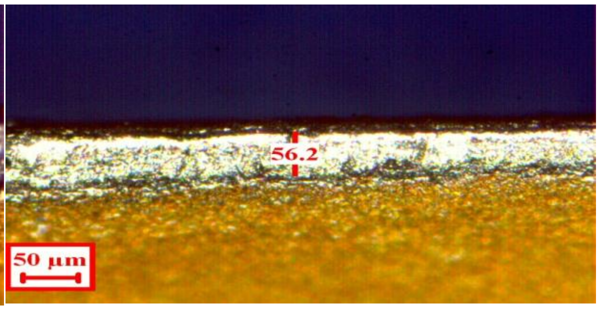




(c): PVD tool B dry condition

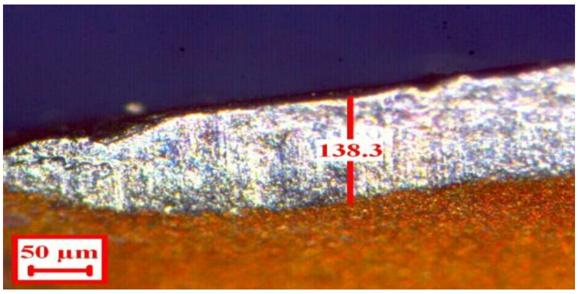
(d): PVD tool B MQL condition

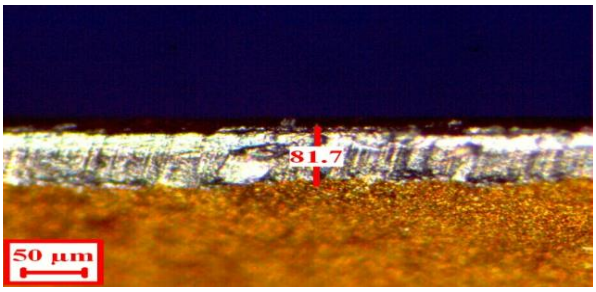




(e): CVD tool A dry

(f): CVD tool A MQL condition

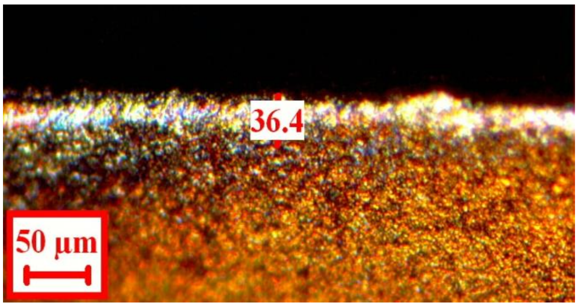


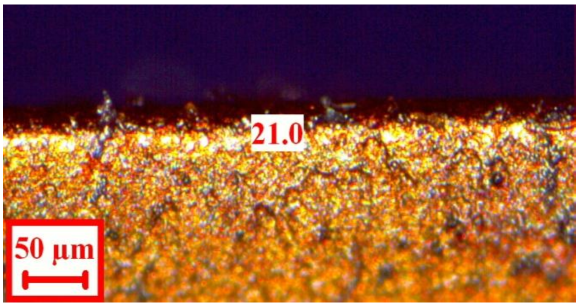


(g): CVD tool B dry condition

(h): CVD tool B MQL condition

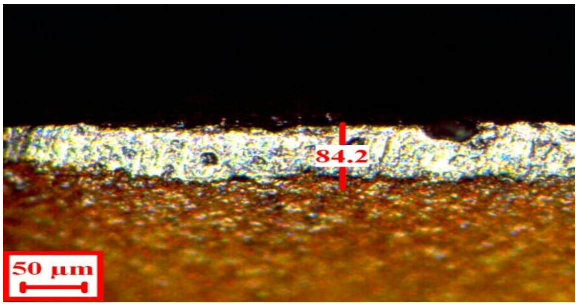
Figure B.2: Microscopy of tool wear for CVD and PVD insert in dry and MQL conditions was shown (in graphs a, b, c, d, e, f, g and h) after 4.5 min at fixed feed rate of 12 mm/min, depth of cut of 3 mm and cutting speed of 200 m/min.

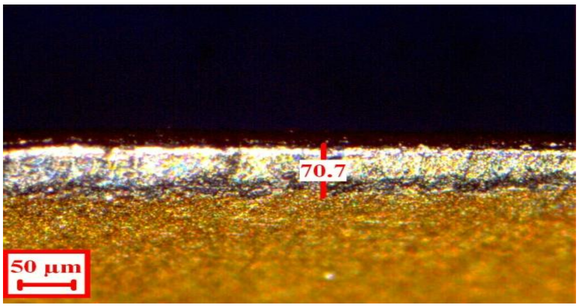




(a): PVD tool B dry condition

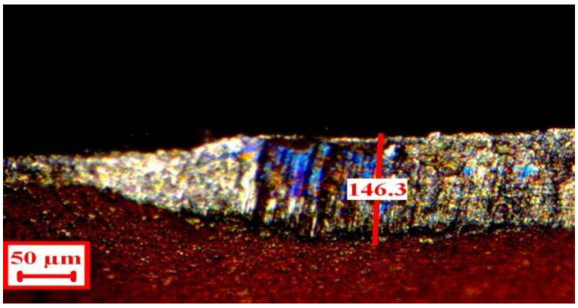
(b): PVD tool B MQL condition

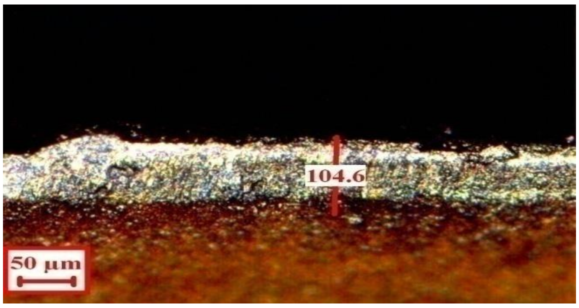




(c): CVD tool A dry condition

(d): CVD tool A MQL condition

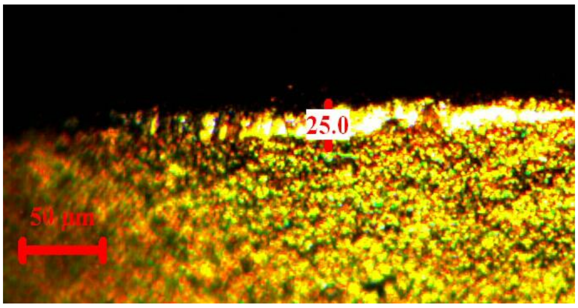


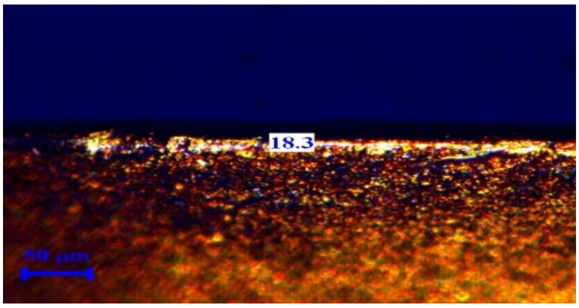


(e): CVD tool B dry condition

(f): CVD tool B MQL condition

Figure B.3: Microscopy of tool wear for CVD and PVD insert in dry and MQL conditions was shown (in graphs a, b, c, d, e, f, g and h) after 4.5 min at fixed feed rate of 12 mm/min, depth of cut of 3 mm and cutting speed of 200 m/min.

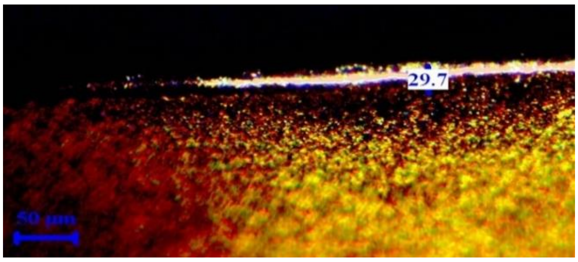


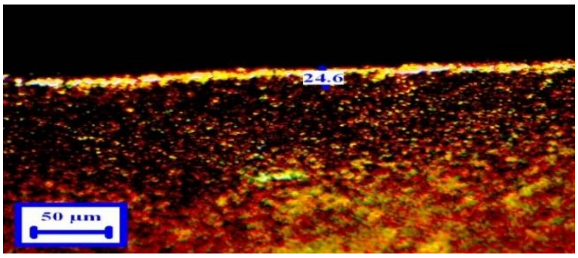


(a) PVD 1025 dry condition

(b) PVD 1025 MQL condition

(A)

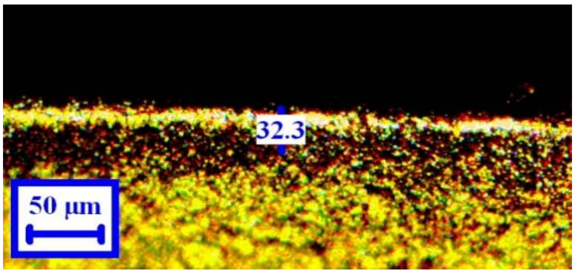


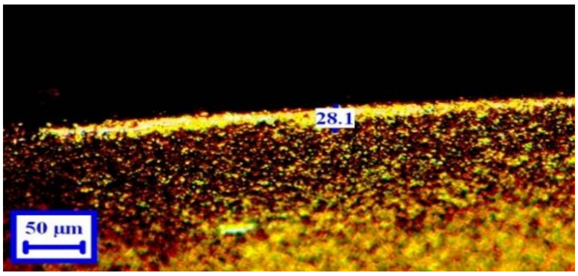


(a) PVD 1025 dry condition

(b) PVD 1025 dry condition

(B)

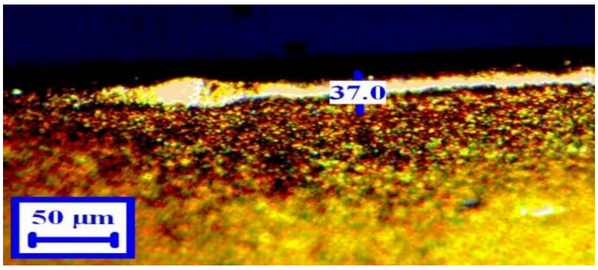


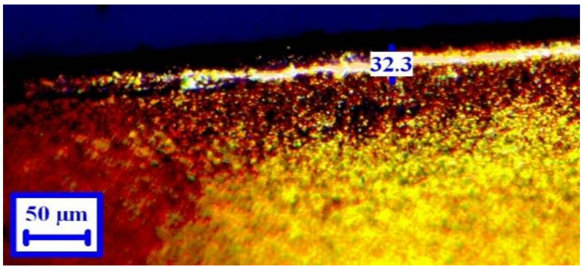


(a) PVD 1025 dry condition

(b) PVD 1025 MQL condition

(C)

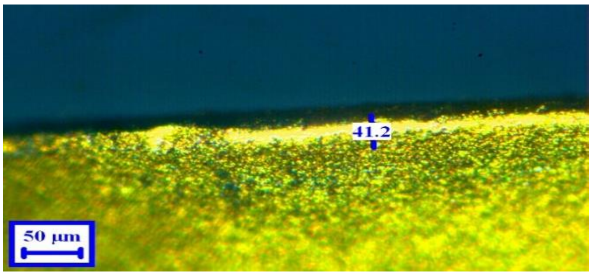


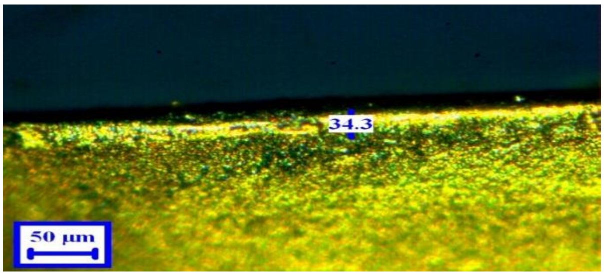


(a) PVD 1025 dry condition

(b) PVD 1025 MQL condition

(D)



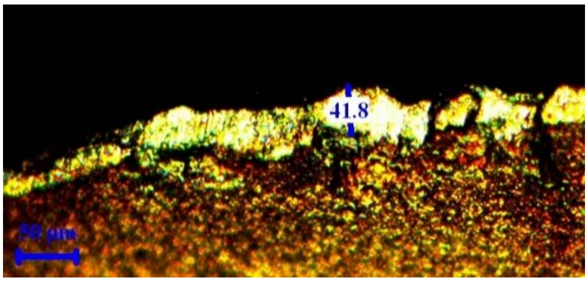


(b) PVD 1025 dry condition

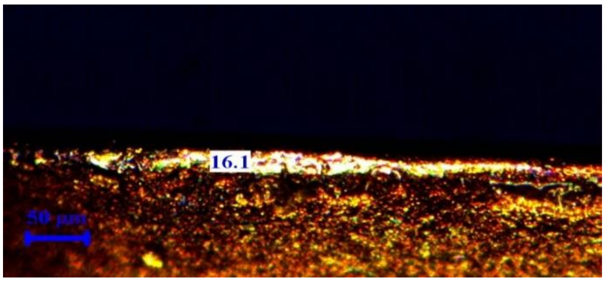
(b) PVD 1025 MQL condition

(E)

Figure B.4: Microscopy of tool wear for PVD 1025 insert in dry and MQL conditions was shown (in graphs a and b) at fixed feed rate of 12 mm/min, depth of cut of 1 mm and cutting speed of 150 m/min (A) at 4.5 min (B) at 9 min (C) at 13.5 min (D) at 18 min (E) at 22.5 min.

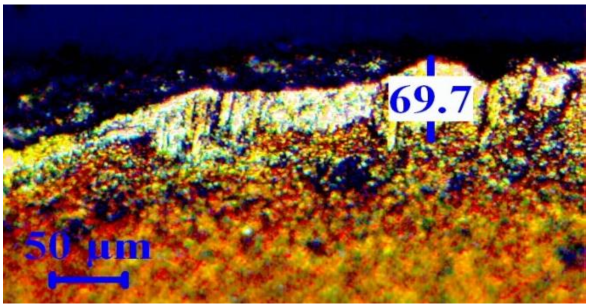


(a) PVD 1025 dry condition

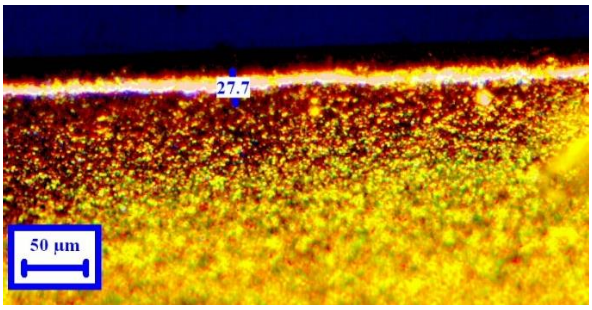


(b) PVD 1025 MQL condition

(A)

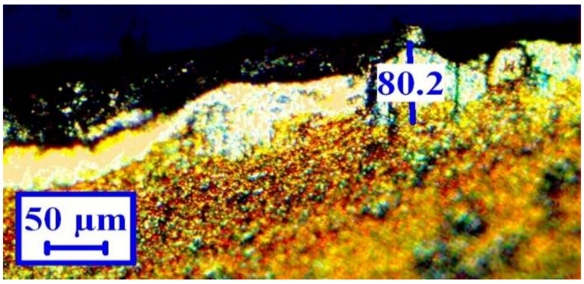


(a) PVD 1025 dry condition

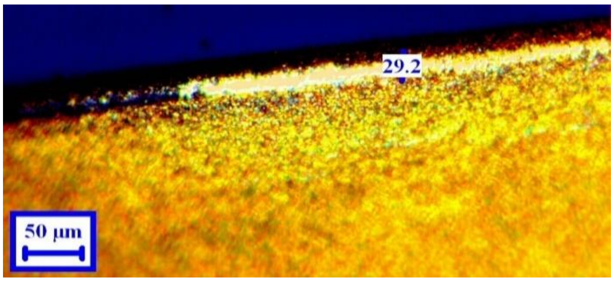


(b) PVD 1025 MQL condition

(B)

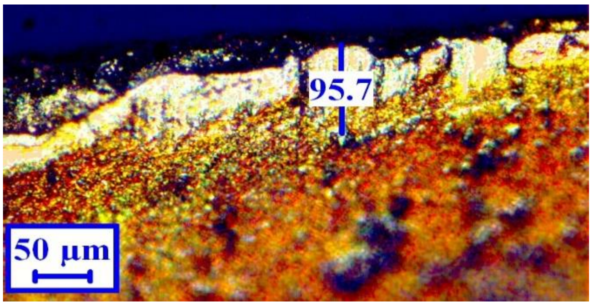


(a) PVD 1025 dry condition

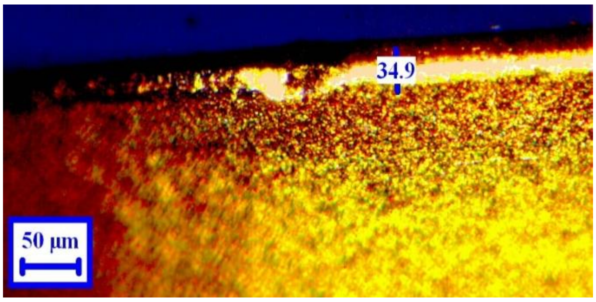


(b) PVD 1025 MQL condition

(C)

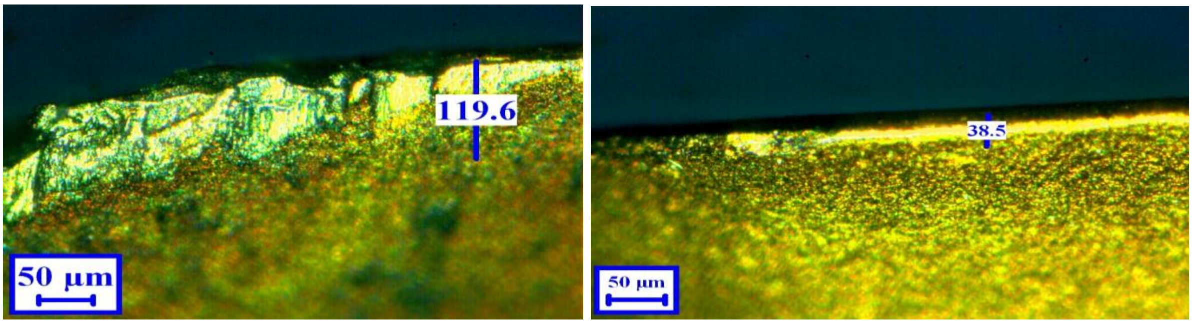


(a) PVD 1025 dry condition



(b) PVD 1025 MQL condition

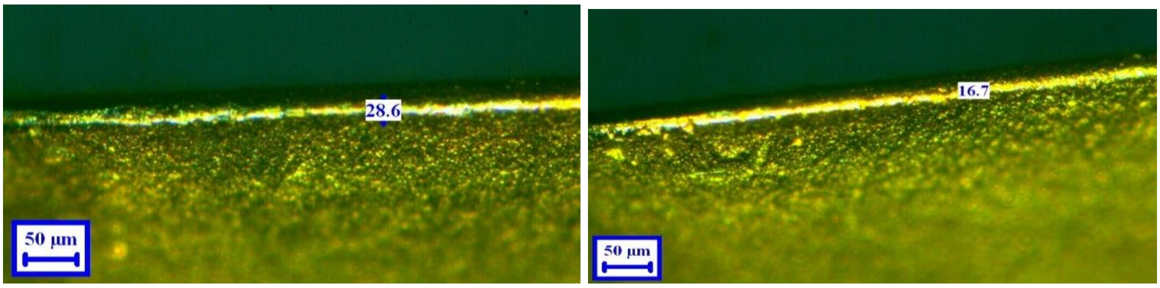
(D)



(a) PVD 1025 dry condition (b) PVD 1025 MQL condition

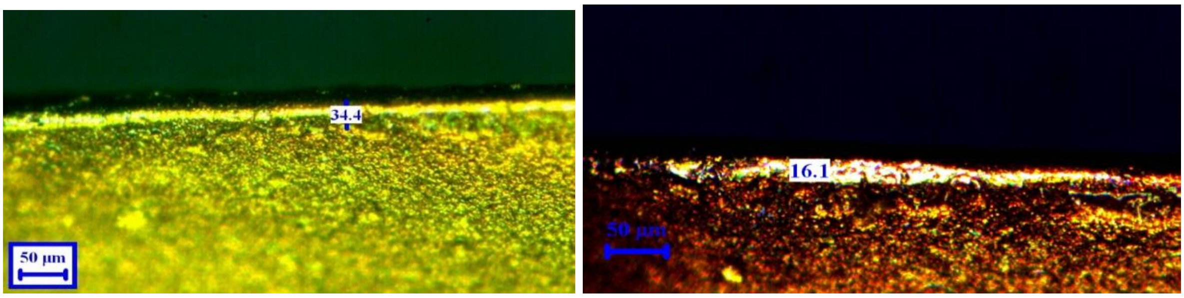
(E)

Figure B.5: Microscopy of tool wear for PVD 1025 insert in dry and MQL conditions was shown (in graphs a and b) at fixed feed rate of 12 mm/min, depth of cut of 1 mm and cutting speed of 175 m/min (A) at 4.5 min (B) at 9 min (C) at 13.5 min (D) at 18 min (E) at 22.5 min.



(a) PVD 1025 dry condition (b) PVD 1025 dry condition

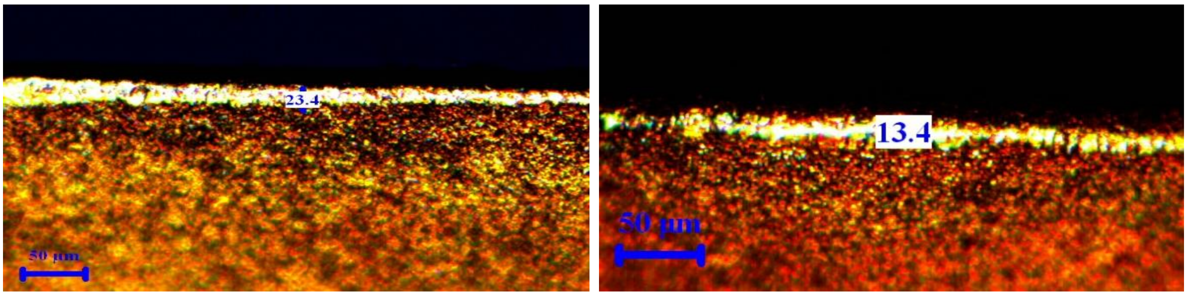
(A)



(a) PVD 1025 dry condition (b) PVD 1025 dry condition

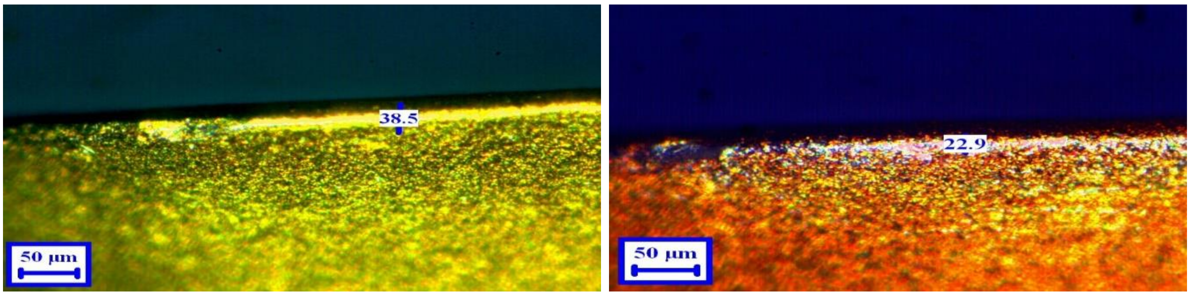
(B)

Figure B.6: Microscopy of tool wear for PVD 1025 insert in dry and MQL conditions was shown (in graphs a and b) at fixed feed rate of 12 mm/min, depth of cut of 1 mm and cutting speed of 200 m/min (A) at 4.5 min (B) at 9 min



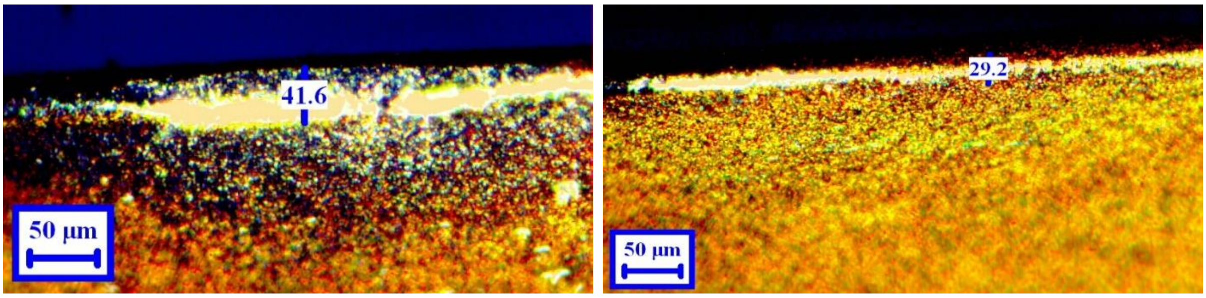
(a) PVD 1030 dry condition (b) PVD 1030 MQL condition

A)



(a) PVD 1030 dry condition (b) PVD 1030 MQL condition

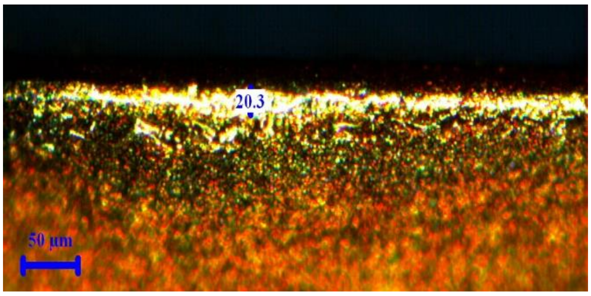
(B)

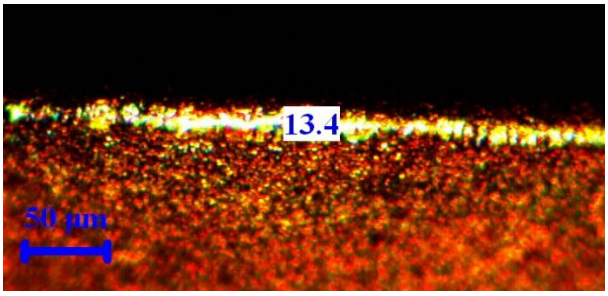


(a) PVD 1030 dry condition (b) PVD 1030 MQL condition

(C)

Figure B.7: Microscopy of tool wear for PVD 1025 insert in dry and MQL conditions was shown (in graphs a and b) at fixed feed rate of 12 mm/min, depth of cut of 1 mm and cutting speed of 175 m/min (A) at 4.5 min (B) at 9 min (C) at 13.5 min

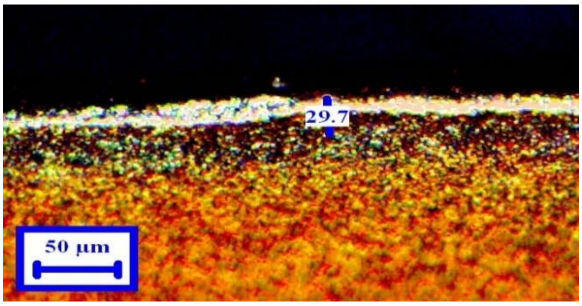


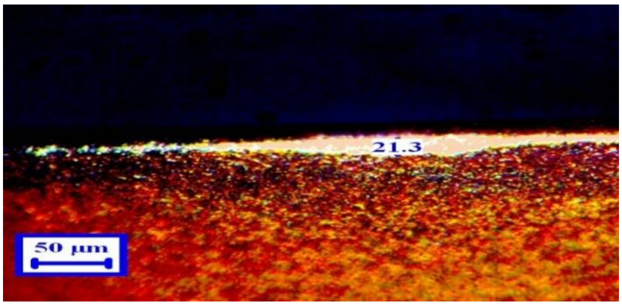


(a) PVD 1030 dry condition

(b) PVD 1030 MQL condition

(A)

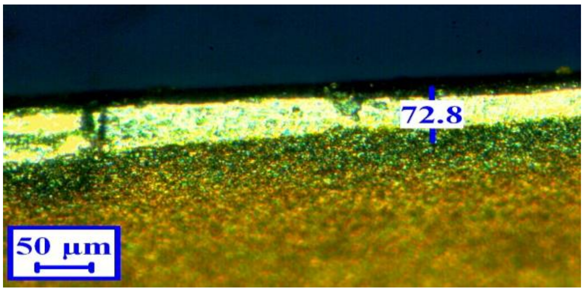


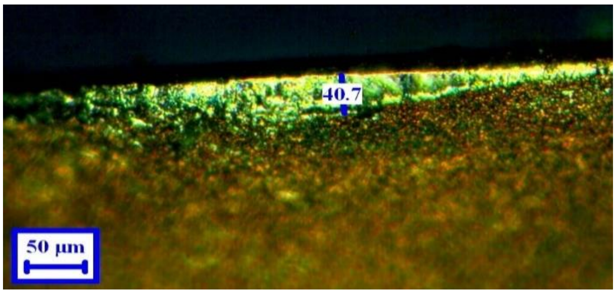


(a) PVD 1030 dry condition

(b) PVD 1030 MQL condition

(B)



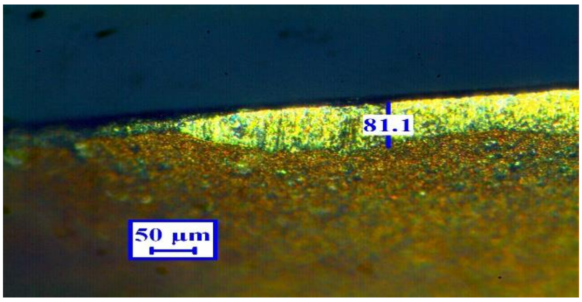


(a) PVD 1030 dry condition

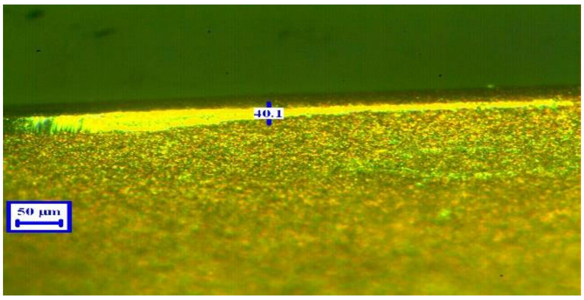
(b) PVD 1030 MQL condition

(C)

Figure B.8: Microscopy of tool wear for PVD 1030 insert in dry and MQL conditions was shown (in graphs a and b) at fixed feed rate of 12 mm/min, depth of cut of 1 mm and cutting speed of 200 m/min (A) at 4.5 min (B) at 9 min (C) at 22.5 min

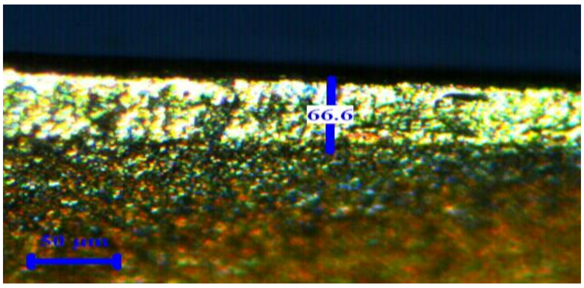


(a) PVD 1030 dry condition

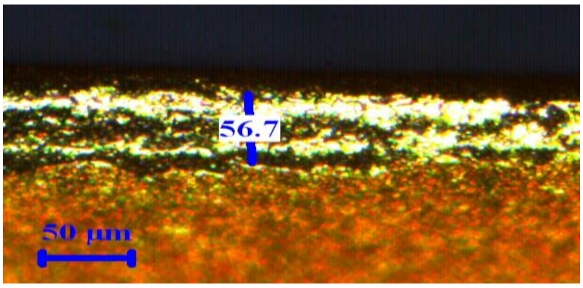


(b) PVD 1030 MQL condition

Figure B.9: Microscopy of tool wear for PVD 1030 insert in dry and MQL conditions was shown (in graphs a and b) at fixed feed rate of 12 mm/min, depth of cut of 1 mm and cutting speed of 200 m/min at 18.5 min.

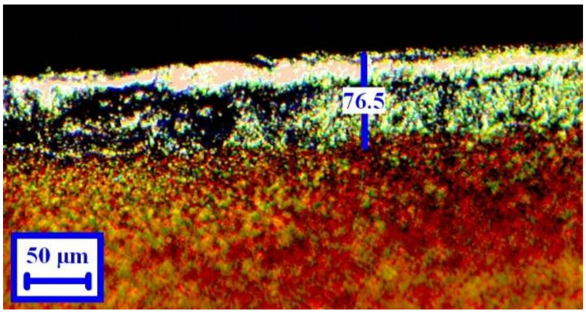


(a) CVD 4240 dry condition

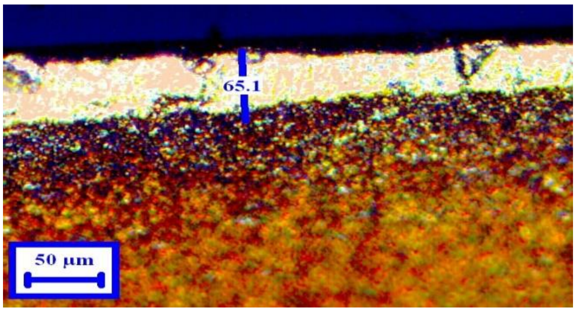


(b) CVD 4240 MQL condition

(A)

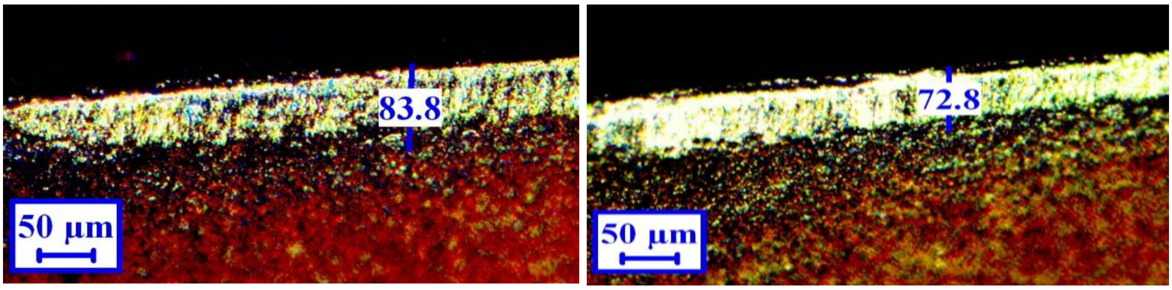


(a) CVD 4240 dry condition



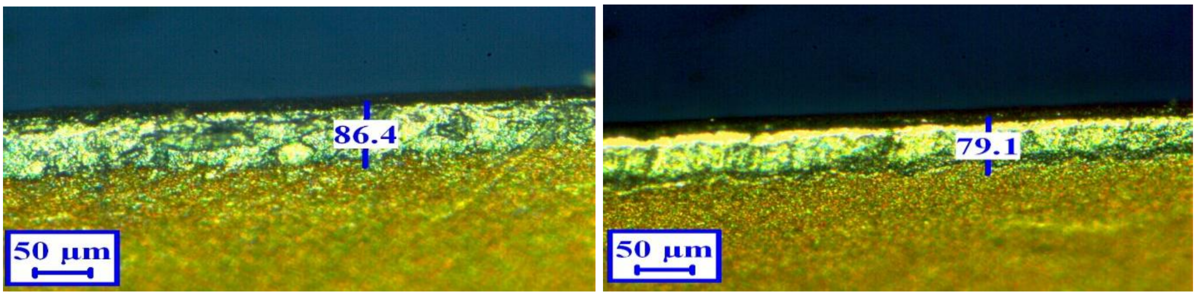
(b) CVD 4240 MQL condition

(B)



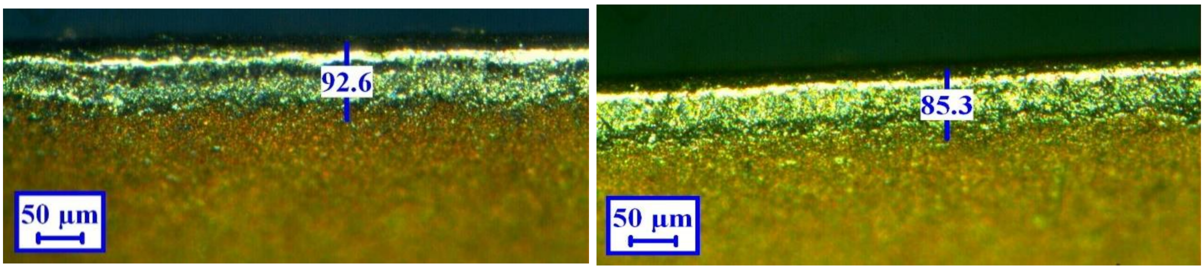
(a) CVD 4240 dry condition (b) CVD 4240 MQL condition

(C)



(a) CVD 4240 dry condition (b) CVD 4240 MQL condition

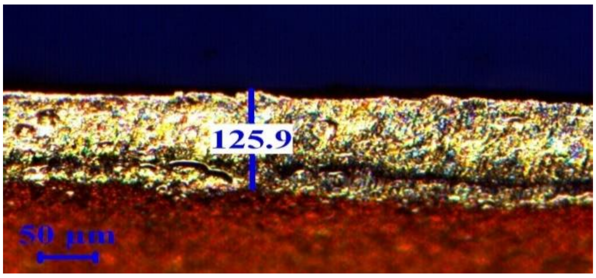
(D)



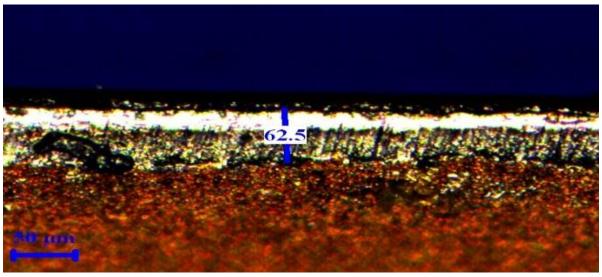
(a) CVD 4240 dry condition (b) CVD 4240 MQL condition

(E)

Figure B.10: Microscopy of tool wear for CVD 4240 insert in dry and MQL conditions was shown (in graphs a and b) at fixed feed rate of 12 mm/min, depth of cut of 1 mm and cutting speed of 175 m/min (A) at 4.5 min (B) at 9 min (C) at 13.5 min (D) at 18 min (E) at 22.5 min.

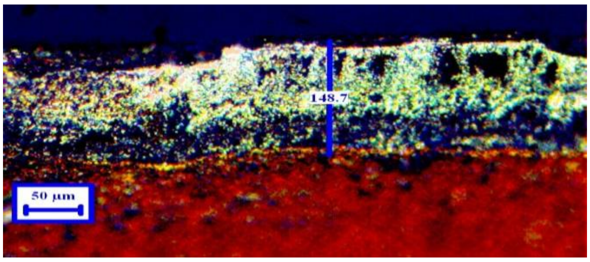


(a) CVD 4240 dry condition

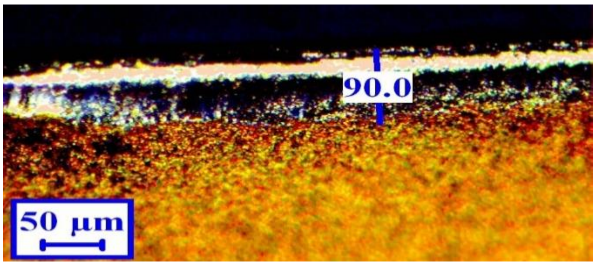


(b) CVD 4240 MQL condition

(A)

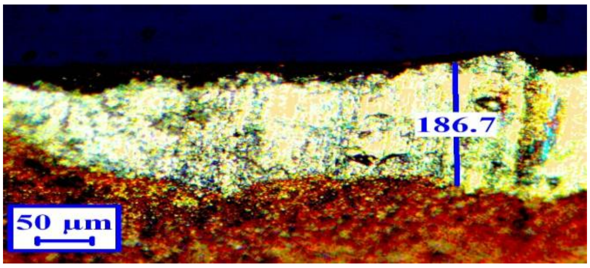


(a) CVD 4240 dry condition

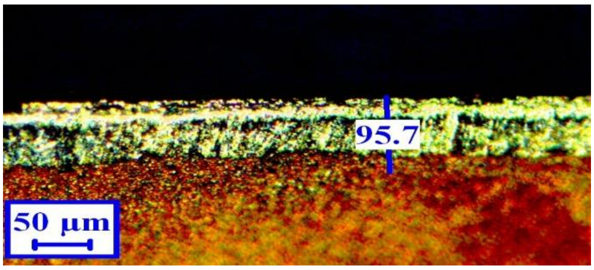


(b) CVD 4240 MQL condition

(B)

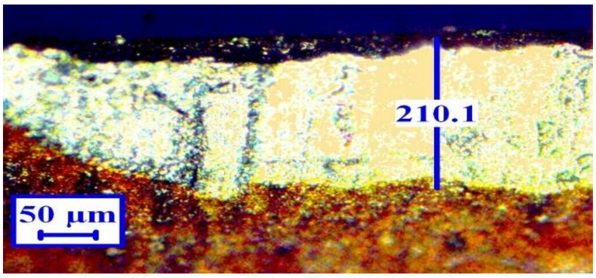


(a) CVD 4240 dry condition

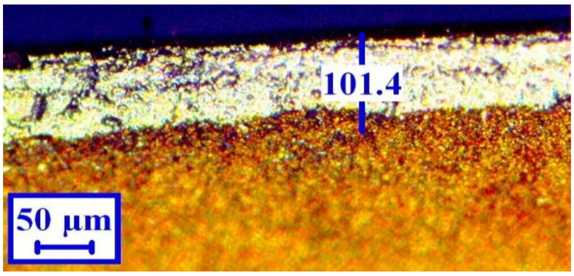


(b) CVD 4240 MQL condition

(C)

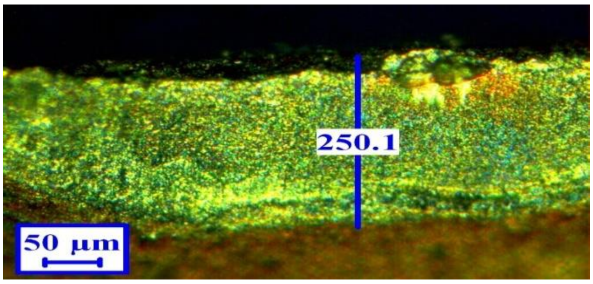


(a) CVD 4240 dry condition

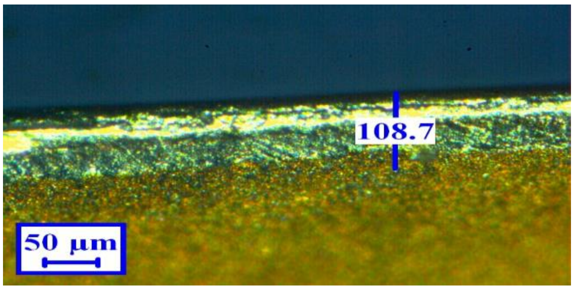


(b) CVD 4240 MQL condition

(D)



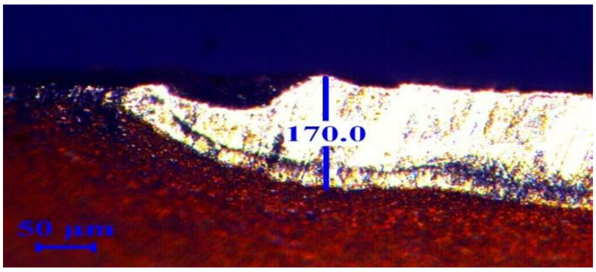
(a) CVD 4240 dry condition



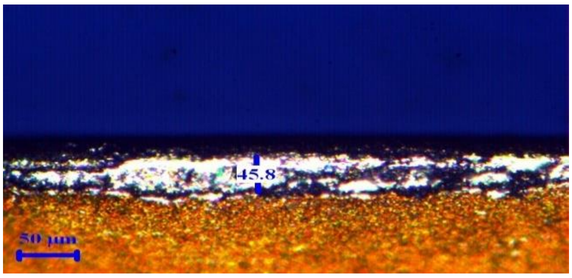
(b) CVD 4240 MQL condition

(E)

Figure B.11: Microscopy of tool wear for CVD 4240 insert in dry and MQL conditions was shown (in graphs a and b) at fixed feed rate of 12 mm/min, depth of cut of 1 mm and cutting speed of 200 m/min (A) at 4.5 min (B) at 9 min (C) at 13.5 min (D) at 18 min (E) at 22.5 min.

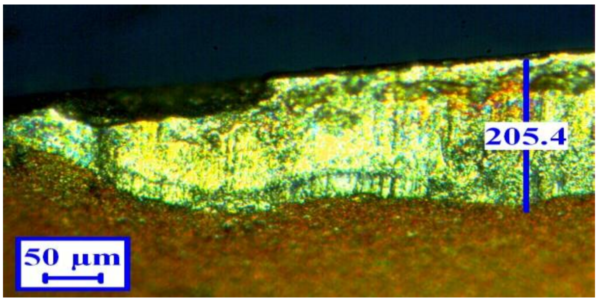


(a) CVD 4240 dry condition

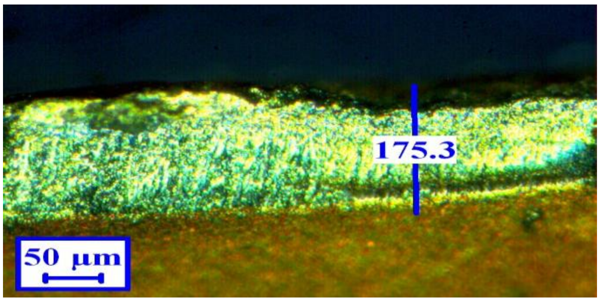


(b) CVD 4240 MQL condition

(A)



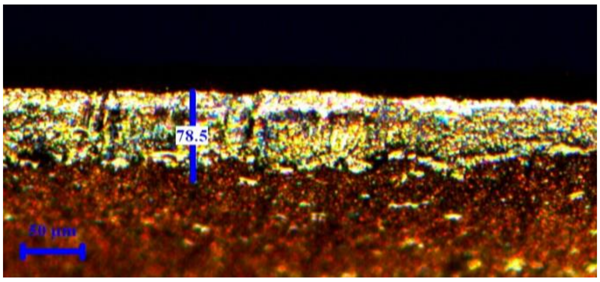
(a) CVD 4240 dry condition

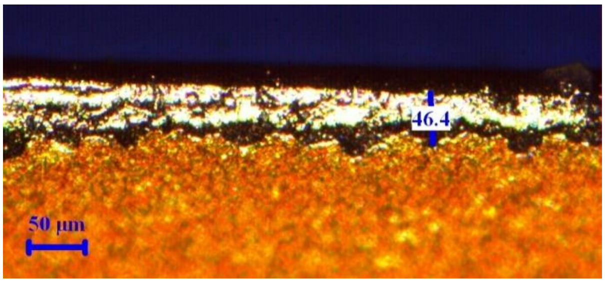


(b) CVD 4240 MQL condition

(B)

Figure B.12: Microscopy of tool wear for CVD 4240 insert in dry and MQL conditions was shown (in graphs a and b) at fixed feed rate of 12 mm/min, depth of cut of 1 mm and cutting speed of 225 m/min (A) at 4.5 min (B) at 22.5 min.

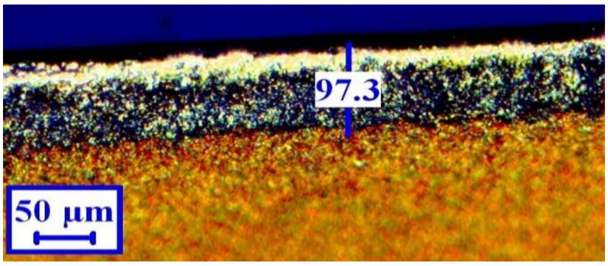


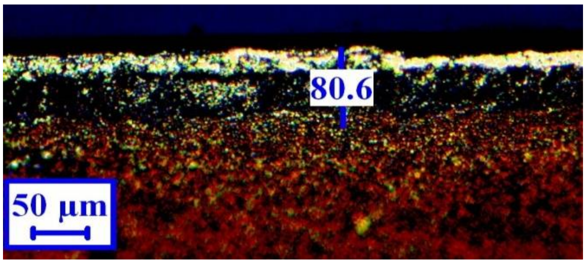


(a) CVD 4230 dry condition

(b) CVD 4230 MQL condition

(A)

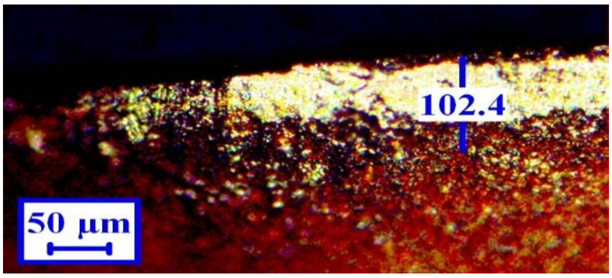


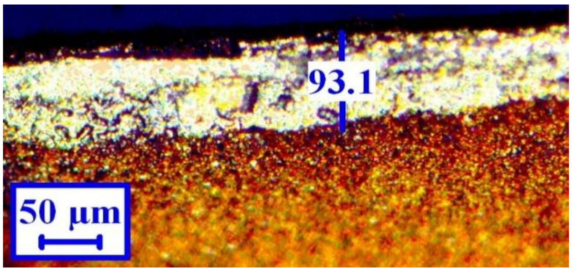


(a) CVD 4230 dry condition

(b) CVD 4230 MQL condition

(B)

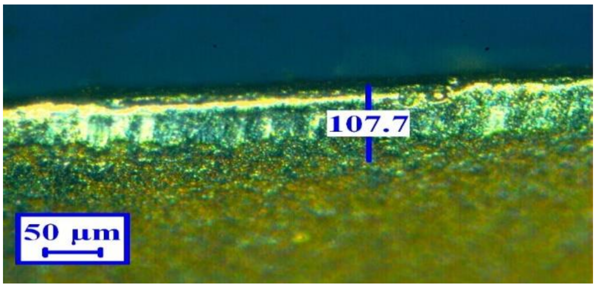


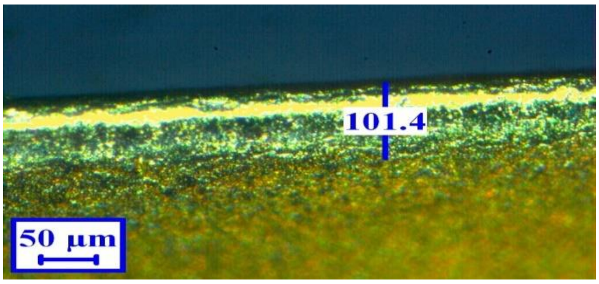


(a) CVD 4230 dry condition

(b) CVD 4230 MQL condition

(C)



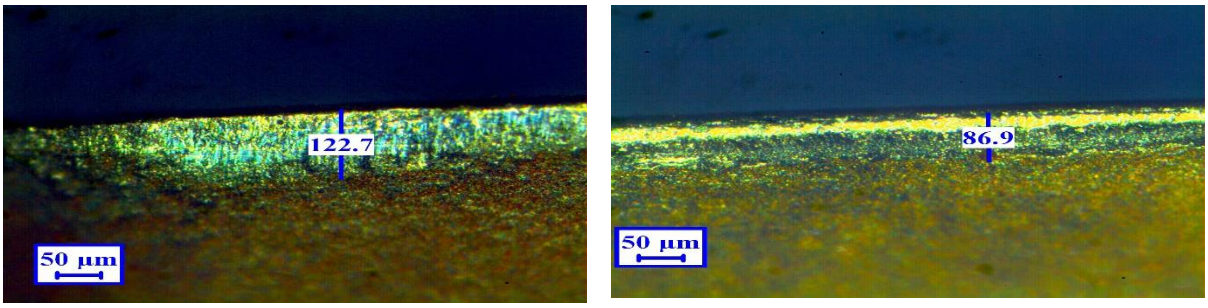


(a) CVD 4230 dry condition

(b) CVD 4230 MQL condition

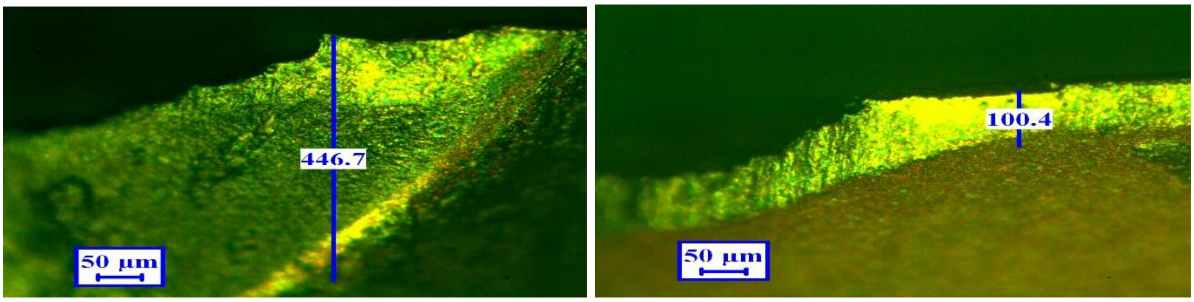
(D)

Figure B.13: Microscopy of tool wear for CVD 4230 insert in dry and MQL conditions was shown (in graphs a and b) at fixed feed rate of 12 mm/min, depth of cut of 1 mm and cutting speed of 200 m/min (A) at 4.5 min (B) at 9 min (C) at 13.5 min (D) at 18 min



(a) CVD 4230 dry condition (b) CVD 4230 MQL condition

Figure B.14: Microscopy of tool wear for CVD 4230 insert in dry and MQL conditions was shown (in graphs a and b) at fixed feed rate of 12 mm/min, depth of cut of 1 mm and cutting speed of 225 m/min at 18 min.



(a) CVD 4230 dry condition (b) CVD 4230 MQL condition

Figure B.15: Microscopy of tool wear for CVD 4230 insert in dry and MQL conditions was shown (in graphs a and b) at fixed feed rate of 12 mm/min, depth of cut of 1 mm and cutting speed of 250 m/min at 9 min.