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Performance Evaluation of Cutting Tools using Minimum Quantity Lubrication (MQL) System during the Machining of Hardened Steel (AISI 1040) In Different Conditions

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ABSTRACT

Machining process costs contribute largely to the total cost incurred in producing a component. Due to improper application of cutting fluids, cutting tools become susceptible to wear and undesired machined parts are produced. Adoption of the Minimum Quantity Lubrication (MQL) system helps in improving the machining process thus providing cleaner production and better-finished products. In this research study, the effect of MQL system was observed in machining hardened steel (AISI 1040). A turning operation was performed in a lathe machine. The turning operation was performed both in dry condition and in MQL condition. Regarding MQL system, three kinds of flow rates (0.2,0.4 and 0.6 gm/min) of cutting fluid were adopted. For dry condition and each flow rate in MQL system, the values of chip reduction co-efficient were evaluated by varying cutting velocity. After the machining process, the effects of dry condition system and MQL system on chip formation and cutting tool were evaluated. It was observed that adoption of MQL system greatly provide neater production than dry condition machining.

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1. INTRODUCTION

The machining process is an important part of the manufacturing of metal components such as mold and die. A research study indicated that the costs associated with the procurement of raw materials, assembly of the components, heat treatment, and machining process in producing dies were 20%, 10%, 5%, and 65% respectively. The study showed that it was more efficient to use MQL machining to reduce cutting temperatures, which resulted in better chip–tool interaction, than dry machining (Dhar et al., 2007). In another study, vegetable oil was used as a base fluid because it is biodegradable and does not pollute the environment. Other vegetable oils can't compare to the lubricating properties of castor oil, but its poor flow and high viscosity prevent it from finding widespread use in industry. As a base oil, castor oil was combined with six other types of vegetable oils (Guo et al., 2017). Findings from a research study revealed that MQL could be considered a replacement for dry cutting, while it could also be considered as an alternative to flood cooling because of the drastic reduction (1/300,000 times) in lubricant consumption and especially when the operator's physiology and the working environment were at stake. (Rahman et al., 2002). MQL machining outperformed both dry and wet machining in terms of chip generation and tool–chip interaction because the cutting zone temperature was significantly reduced during MQL machining. The reduced tool wears also resulted in improved tool life and surface polish, according to the results. (Khan et al., 2009).

Definition of Minimum Quantity Lubrication System

MQL may be considered an economical and environmentally compatible lubrication technique for low speed, feed rate, and depth of cut. Experiments conducted by (Dhar et al., 2007) indicated that using vegetable oil as a cutting lubricant through the MQL technique provided benefits mainly by reducing the cutting temperature, improving the surface finish, and dimensional accuracy and cutting forces. The use of cutting fluids during machining operations creates several occupational health risks and many environmental effects as well. The machining fraternity has to cut the environmental burdens without sacrificing the production rate and product quality. This situation has encouraged the development of new machining research areas such as machining using cryogenic liquids, dry machining with high-performance cutting inserts and innovative coating techniques, and machining with a limited quantity of cutting fluid-like using minimum quantity lubrication (MQL).

Importance of Minimum Quantity Lubrication System

Traditional cutting fluids have been replaced in green manufacturing processes with minimal quantity lubrication (MQL) in order to avoid the environmental and health issues associated with conventional cutting fluid (Wu et al., 2022). Green manufacturing is one of the major themes in manufacturing in recent years due to increased environmental awareness and strict protection laws and health regulations for occupational safety. Environmental and occupational health hazard problems in metal cutting industry are mainly related to the use and disposal of cutting fluids. Cutting fluids are used in machining operations to reduce the friction in contact zone and thereby reduce force and power in machining, increase tool life, improve surface finish and chip removal, and reduce thermal distortion and subsurface damage (DeVries, 1991). However, notwithstanding the above-mentioned advantages, the use of cutting fluids suffers from serious drawbacks of operator health hazard as well as environmental and economic problems. Improper disposal of cutting fluids in rivers, lakes and oceans pollutes land, water and air. This adversely affects the growth of plants and animals, and disturbs the whole environment (Jiang et al., 2008). Contact of cutting fluid with skin and inhalation of its vapors causes skin and respiratory problems due to the presence of extreme pressure additives, emulsifiers, biocides, rust inhibitors, stabilizers, fragrances, and contaminants in it. Also, cutting fluid particles remain suspended in the environment for an extended period of time (Sutherland et al., 2000). This not only affects the operators but also other employees who are not in direct contact with cutting fluids.

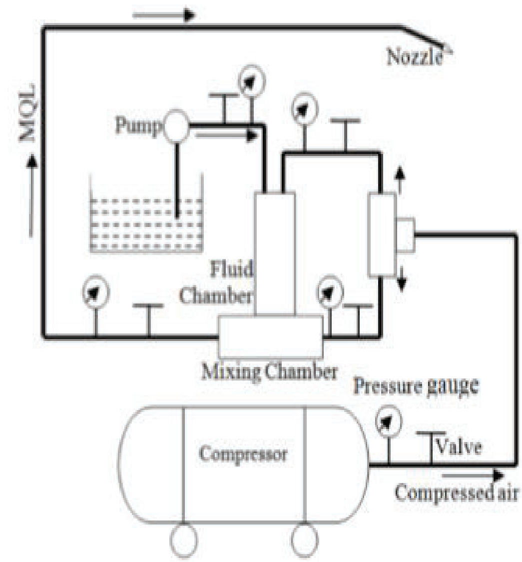

Figure 1.1: Schematic View of MQL System (Dhar et al., 2007).

Cutting fluids used in MQL System

For cooling the cutting tool and workpiece, lubricating the tool-workpiece interface, and eliminating chips from the cutting zone, cutting fluid is critical in any metal cutting operation. Minimum quantity lubrication (MQL) is one of the various coolant application technologies that has recently attracted the attention of researchers because it uses less coolant than flood cooling by spurting a mixture of compressed air and cutting fluid. The MQL approach has been proven to be appropriate for 'green' machining because it meets all of the requirements (Said et al., 2019). Turning coolants should be free from fatty materials that tend to load the wheel, thus affecting the finish on the machined part. Soluble coolants should contain rust preventive constituents to prevent corrosion. Soluble oil and synthetic ester oil are two viable alternatives. Soluble oils, based on extract from plants are biodegradable and non-toxic, and have low volatility. Molecules of these oils are long, heavy and dipolar in nature and provide good boundary lubrication properties and greater capacity to absorb pressure. Higher viscosity index provides stable lubrication in operating temperature range and higher flash point provides opportunity to increase metal removal rate due to reduced smoke formation and fire hazard. However, they have poor oxidation stability which makes them susceptible to radical attacks. Some synthetic esters, synthesized from a specific polyhydric alcohol. These synthetic esters have high biodegradability, excellent oxidation stability, good storage stability and satisfactory cutting performance. Investigated synthetic esters were suggested as satisfactory MQL cutting fluid on the basis of cutting performance and optimal fluid for MQL machining on the basis of biodegradability, oxidation and storage stability. MQL is an environment friendly technique as the soluble oils are used in very small quantities. However, contrary to this reported that airborne mist levels in MQL were comparable with MQL System application and were proportional to the volume of oil entering the system. As one of the main purposes of MQL assisted machining is to reduce the health hazard associated with MQL System cooling so, mass concentration and particle size as well as composition and physical state of mist requires serious attention.

Effect of nozzle position and spraying method on MQL performance

The machining effectiveness in MQL machining largely depends on the position of the nozzle as it determines the penetration of the cutting fluid in chip tool interface. In a study, It was found that in MQL, cutting fluid was not able to reach in the cutting area when the aerosol was directed on the rake face as no trace of lubricant was seen on the worn surface. However, when the cutting fluid was applied on the flank face, traces of lubricant compounds were found on the worn surface indicating penetration of the cutting fluid in chip-tool interface. Apart from this, inclination of nozzle also significantly affected the process (Attanasio et al., 2006) .

Effect of Minimum Quantity Lubrication (MQL) on Cutting Forces

Cutting forces with MQL were found less than in dry cutting but higher than MQL System cutting in turning of AISI 1045 steel. At lower cutting speeds lubrication was effective but with the increase in cutting speed, lubrication effectiveness decreases. As a result, the reduction in cutting forces with MQL also decreases. MQL was found to be most effective in reducing the tangential cutting force among the feed, radial, and tangential force components. In the hard turning of AISI 4340 steel, cutting force was found lowest with MQL as compared to dry turning. The cutting force in the turning of 6061 aluminum alloy with MQL was less than that of under dry machining. In turning of AISI 1045 steel, MQL System turning generally produced lower cutting forces as compared to MQL. However, the difference was not significant. Exit pressure was the most significant parameter affecting the cutting force followed by the depth of cut and feed. An increase in nozzle pressure increased the exit velocity of cutting fluid resulting in better penetration and thus a reduction in cutting force (Kumar & Ramamoorthy, 2007). In brass turning, slightly higher cutting power was observed with MQL lubrication at 50 ml/h and flood lubrication at 2,000 ml/h as compared to almost the same power at a flow rate of 100 ml/h and 200 ml/h. The optimal quantity of lubricant, cutting speed, and feed rate were determined for simultaneously minimizing surface roughness and specific cutting force by using the Taguchi method and utility concept (Gaitonde et al., 2008). It was further reported that feed rate was the most significant factor followed by quantity of lubricant and cutting speed in optimizing the machinability characteristics.

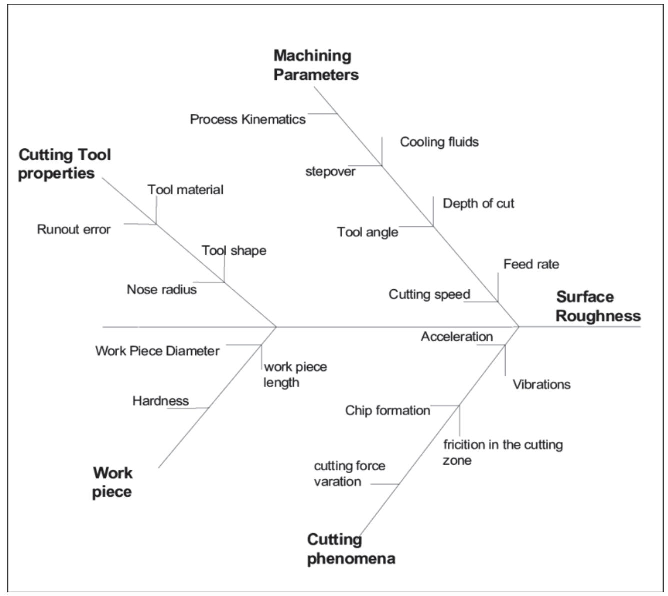

Figure 1.2: Fishbone Diagram of Machining System

Effect of Minimum Quantity Lubrication (MQL) on chip morphology

Chip morphology and its appearance represent the interaction between the chip-tool interface. A bright and smooth back surface of the chip represents favorable chip-tool interaction and elimination of built-up edge formation. In a study, the turning of AISI-1040 steel was performed with the help of MQL application. It was observed that the cutting temperature was effectively reduced and blue-colored, spiral-shaped chips produced under dry conditions became metallic-colored and arc-shaped (half turn). Also, the back surface of the chip under MQL was found much brighter and smoother indicating favorable chip tool interaction and elimination of built-up edge formation. In turning of 100Cr6, more up-curled chips were obtained with emulsion as compared to MQL. Chips obtained with MQL and compressed air had almost the same radius of curvature, whereas, chips obtained in dry cutting had the largest radius of curvature. Chips obtained in dry cutting were wider than those of obtained with other methods due to side flow in the shear plane. Those chips had side curl due to differences in speed at the outer and inner diameter of the workpiece. In the finish turning of Inconel 718, long continuous curled tubular chips were obtained during dry cutting, whereas, the application of cooled air and cooled air with MQL lead to short continuous flat tubular chips representing the favorable chip morphology (Su et al., 2007). In intermittent turning of aluminum alloy, MQL with oil film on water was found more effective than MQL with oil due to the associated chilling effect. The contact width on rake face was found slightly smaller with flood cooling and MQL with oil film on water than with dry cutting and MQL with oil. Also, more tightly curled chips were formed with flood cooling and MQL with oil film on water. It was also mentioned that MQL with oil film on water provides good lubrication when synthetic ester is used as lubricant.

Effect of Minimum Quantity Lubrication (MQL) System on surface roughness

Surface roughness increases slowly with MQL as compared to dry and MQL System machining. However, in the machining of 6061 aluminum alloy surface roughness obtained by MQL is found to lie between the values obtained by dry cutting and flooded conditions. Adhesion of material on the work surface plays quite an important role in deciding the surface roughness. At higher cutting speed, adhesion of adhered material from the tool to the work surface increases and thus resulting in a higher value of surface roughness. air pressure, nozzle diameter, cutting speed, feed rate, and depth of cut, all the parameters except supplied air pressure significantly affect the surface roughness. In the hard turning of AISI4340, surface roughness is affected the most by feed as generally observed in machining operations and then by nozzle pressure, type of coating, and amount of cutting fluid.

Effect of MQL system on Tool Wear and Tool Life

Cutting tools often failed prematurely, randomly, and catastrophically by mechanical breakage and plastic deformation due to the intensive pressure and temperature and/or dynamic loading at the tool tip. An Increase in chip-tool interface temperature might cause the wear mechanism to change from abrasion to adhesion or from adhesion to diffusion (Puji Pranoto, 2016). As compared to dry cutting, 78% and 124% improvement in tool life was obtained with cooled air, and cooled air with MQL respectively in finish turning of Inconel 718 (Su et al., 2007). In a study, a comparative study of tool life by MQL application on rake and flank face of the tool in finish turning of 100Cr6 was done by (Attanasio et al., 2006). While using specially designed nozzles for MQL assisted finish turning of Inconel 718, it was found that control of oil mist flow and decrease in distance between nozzle and tool tip enhanced the cutting performance of MQL particularly in µLL range (Obikawa et al., 2008). No benefit in flank wear and surface roughness with MQL technique in finish turning of AISI 420B steel (Bruni et al., 2006). Similar values of flank wear and surface roughness with dry and minimum volume of oil (MVO) cutting in turning of AISI 52100 hardened steel. Based on this study it was concluded that dry cutting was best for turning of this material.

2. MATERIALS AND METHODOLOGY

The purpose of this research is to evaluate the feasibility of soluble oil as a cutting lubricant through the use of quantity lubricant system (MQL) during turning of hardened mild steel and the performance of coated carbide tools when turning on hardened mild steel to hardness of 28 HRC under MQL system.

Machines and Equipments

The machines and equipment used in the experiment are the following:

a. Lathe Machine: 14 HP, Mansun, Made in Korea. Working Range: 12 feet, 16 inch. Load Capacity: Heavy Load Machine, Spindle Speed: (210-550) rpm
b. Minimum Quantity Lubricant Dispensing Systems:
   Fluid Tank Capacity: 5.5 litre
   Nozzle: 2 pcs convergent nozzle
   Air Compressor Capacity: 2-10 bar
   Flow meter (Rotameter) Capacity: 0.2g/min–2g/min

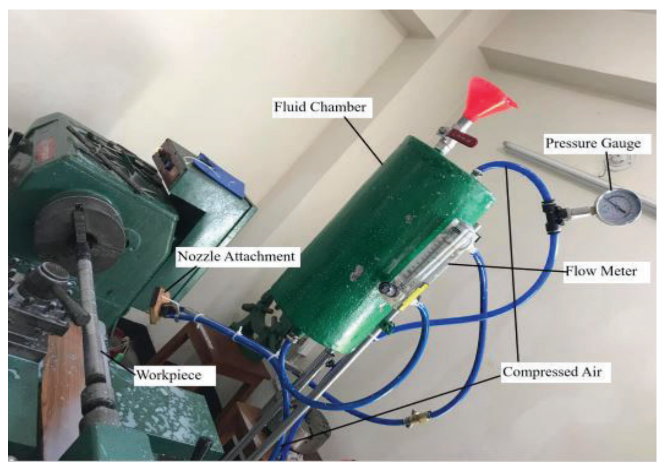

Figure 2.1: Photographic View of Minimum Quantity Lubrication System

Experimental Procedure

Implementation of Minimum Quantity Lubrication system in Lathe Machine.
↓
Hold the workpiece on the Headchuck of Lathe machine.
↓
Initially Start machining with Dry condition then machined with MQL system.
↓
Experimental procedure done with differents turning conditions parameters.
↓
Collecting chip at the machining time for calculating the chip reduction co-efficient.

Figure 2.2: Block Diagram of Experimental Procedure

Experiments was carried out by turning a 101.6 mm diameter and 760mm long rod of AISI-1040 Hardened steel HRC 28 in a powerful and rigid lathe at different cutting velocities (V_c) and feed rate (S_o) under both dry and MQL conditions to study the role of MQL on the machinability characteristics of the work material mainly in respect of chip reduction co-efficient deviation. The experimental conditions were dry and MQL. The ranges of the (V_c) and feed rate (S_o) were selected based on the tool manufacturer's recommendation and industrial practices. Depth of cut, being less significant parameter, was kept fixed. The MQL needed to be supplied at high pressure and impinged at high speed through the nozzle at the cutting zone. Considering the conditions required for the present work and uninterrupted supply of MQL at constant pressure around 2.0 bar over a reasonably long cut, an MQL delivery system was designed, fabricated and used. The Photographic view of Minimum Quantity Lubrication System was shown in (Figure 2.1). MQL was expected to provide some favorable effects mainly through the reduction in cutting temperature. The machining chips were collected during all the treatments for studying their nature of interaction with the cutting insert at its rake surface. In the operation there were two types of the chip collected with both cutting conditions with respect to different flow rate and different cutting parameters.

Experimental Condition

There were two cutting medium (Dry and MQL) and in MQL medium there were three kinds of flow rate of cutting fluid. Cutting Speed = (250,350,450) rpm, depth of cut 1 mm and feed rate 0.2, 0.4 and 0.6 mm/rev.

3. RESULTS AND DISCUSSION

In the current research study, the variation of the chip reduction coefficient was observed by varying cutting velocity and cutting conditions. The results obtained from the study were summarized in Table 1.

	Lathe Machine: 14HP Mansun, Made in Korea. Working Range: 12 feet, 16 inch. Capacity: Heavy Load Machine, Spindle Speed: (210-550) rpm
Work specimens Material	Hardened Mild Steel (AISI 1040) to Bulk Hardening and Hardness of 28 HRC
Cutting insert	Integrated Centre Hole Coated Carbide
Velocity, Vc Feed Rate, So Depth of Cut Speed, N	79.01, 110.62, 142.22 m/min 0.2, 0.4, 0.6 mm/rev 0.1 mm 250,350,450 rpm
Cutting Fluid Supply	For MQL cooling – air 6 bar; Flow rate 0.2, 0.4 and 0.6 gm/min, Air pressure on Fluid Chamber 2 bar.
Environment	Dry and Minimum Quantity Lubrication (MQL).

Table 1: Comparison between Cutting velocity, V_c with Chip Reduction Co-Efficient

Cutting Velocity, V_c	Chip Reduction Co-Efficient, ζ			
	Dry condition	0.2 gm./min	0.4 gm./min	0.6 gm./min
79.01 m/min	4.04	4.09	4.16	4.22
110.62 m/min	2.17	2.19	2.22	2.25
142.22 m/min	1.48	1.50	1.52	1.54

Figure 3.1 represents the comparison between Chip Reduction Co- Efficient and Cutting Velocity at Dry Condition, where any kinds of cutting fluids were not used. From the graph, it is revealed that there is negative correlation between cutting velocity and chip reduction co-efficient.

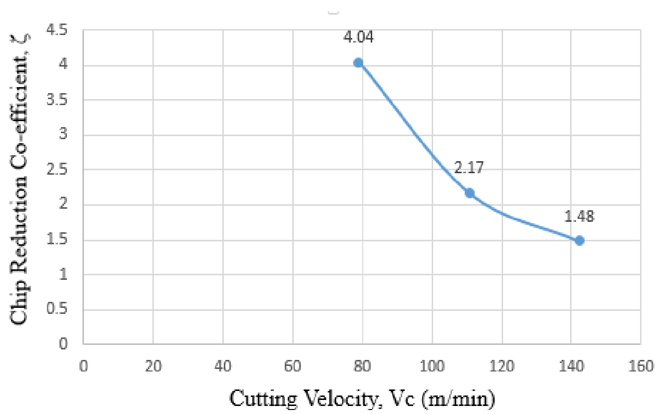

Figure 3.1: Chip Reduction Co-Efficient, ζ vs Cutting Velocity, V_c at Dry Condition

In Figure 3.2, the comparison between Chip Reduction Co-Efficient and Cutting Velocity at MQL Condition was performed using a flow rate of 0.2 gm/min where the chip reduction co-efficient decreases with the increase in cutting velocity.

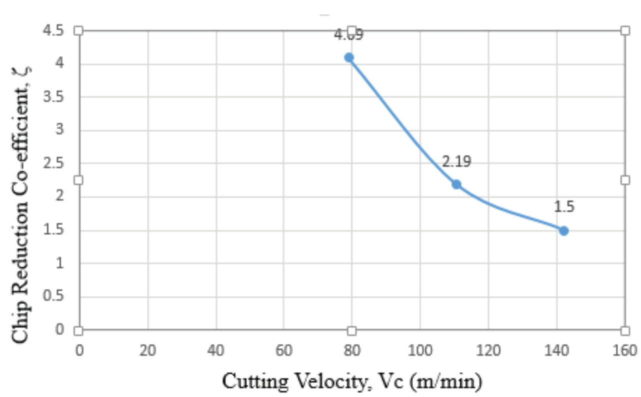

Figure 3.2: Chip Reduction Co-Efficient, ζ vs Cutting Velocity, V_c at MQL Condition (Flow rate=0.2 gm/min)

In Figure 3.3, the comparison between Chip Reduction Co-Efficient and Cutting Velocity at MQL Condition was performed using a flow rate of 0.4 gm/min. Increase in the flow rate of cutting fluid at MQL condition caused increase in chip reduction co-efficient. A negative correlation was observed between cutting velocity and chip reduction co-efficient.

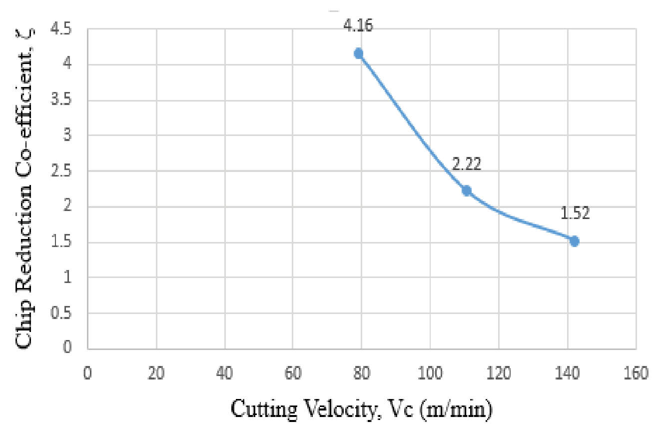

Figure 3.3: Chip Reduction Co-Efficient, ζ vs Cutting Velocity, V_c at MQL Condition (Flow rate=0.4 gm/min)

In Figure 3.4, the comparison between Chip Reduction Co-Efficient and Cutting Velocity at MQL Condition was performed using a flow rate of 0.6 gm/min. Same behavior was observed at this time also between chip reduction co-efficient and cutting velocity.

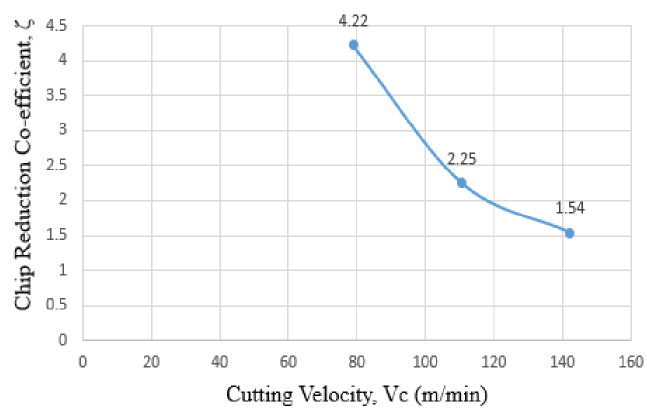

Figure 3.4: Chip Reduction Co-Efficient, ζ vs Cutting Velocity, V_c at MQL Condition (Flow rate=0.6 gm/min)

Figure 3.5: Photographic view of Chips at Dry Condition

Figure 3.6: Photographic view of Chips at MQL Condition

Figure 3.5 and Figure 3.6 provided the comparative view of chips formation between dry conditions vs MQL conditions. Figure 3.5 showed the blue color chip formed during dry condition machining and Figure 3.6 showed the chips formed during MQL condition machining. Due to substantial reduction in cutting zone temperature those chips had no burden color.

Figure 3.7: Photographic view of Cutting Tool at Dry Condition

Figure 3.8: Photographic view of Cutting Tool at MQL Condition

Figure 3.7 showed the photographic view of cutting tool machining with dry condition and Figure 3.8 showed the photographic view of cutting tool machining with MQL condition. Here, it's revealed that dry condition was a threat for cutting tool. Tool wear in dry condition was significantly higher than that of in MQL condition. MQL system provided friendly characteristics to cutting tool. In MQL condition, the required cutting force was relatively less and the interaction between cutting tool and work-piece was relatively smooth.

4. CONCLUSIONS

A better knowledge on the design and fabrication of Minimum Quantity Lubrication (MQL) System in machining hardened Steel was obtained from this research. It is evident from the literature that application of MQL has resulted in better tool life, improved surface finish, reduction in cutting temperature, better chip forms and reduced cutting forces. The findings showed alignment with the results of the previous studies. An experiment performed by using hardened steel as a work-piece revealed that adoption of MQL system can improve the machining process by ameliorating heat transfer problem (Mia et al., 2018). The value of chip thickness reduction co-efficient reduced with the increase in cutting velocity. It was also revealed that tool wear was significantly less while machining with MQL system compared to machining in dry condition. Determination of rationale value of operating parameters such as- orientation of nozzle, air and oil flow rate, air pressure etc. played a vital role in the outcomes achieved by adopting MQL system. level and droplet size as it seems that mist level is assumed lower than flood cooling without knowing the actual mist level. Minimum Quantity Lubrication assisted comparable with MQL System turning than entire system must be restudied and suitable alteration in terms of method of MQL system, machining parameters, etc. should be taken.

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