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Tool Life Predication and Performance Analysis Under Various Cutting Fluid Condition

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ABSTRACT

The modern manufacturing industry is characterized by reduced costs, high precision, and increased productivity. Tool life prediction and performance analysis of the machining process are thus essential in this industry. Cutting fluids play an important role in reducing friction, controlling temperature, increasing surface finish, and increasing tool life during machining processes. The research focuses on the effects of different cutting fluids conditions on surface finish, material removal rate, cutting temperature, and tool life. The dry machining, flood cooling, and Minimum Quantity Lubrication (MQL) techniques have been used in the comparative analysis. Carbide cutting tools are used for turning medium carbon steel materials. Taylor's Tool Life Equation and statistical analysis techniques have been used to analyze the behavior of tools as well as the machining process. As compared to dry and conventional flood cooling methods, the findings reveal that MQL provides a balanced combination of cooling and lubrication, thus increasing the life of tools and improving machining processes. The paper gives recommendations on how to select proper cutting fluid conditions for machining.

Keywords: *Tool Life Prediction, Cutting Fluids, Machining Performance, Tool Wear, MQL, Surface Roughness, Cutting Temperature, Sustainable Manufacturing.*

1. Introduction

The reason for using machining processes lies in their ability to produce parts with great precision, good surface finish, and dimensional accuracy. Therefore, they are vital in the manufacturing industry to produce mechanical parts. Industries such as heavy engineering, automobile industry, aerospace industry, and railways utilize machining processes like turning, milling, drilling, and grinding to produce mechanical parts. Factors that affect the effectiveness of machining processes include workpiece properties, lubrication, cutting tool materials, and machining conditions [1], [2].Tool life is one of the factors affecting machining process economics and productivity. Tool life refers to the period during which a cutting tool will perform effectively until it becomes worn out or fails to function properly. Reduction of cost of production, reduction in machine idle time, and improvement in dimensional accuracy depend on correct tool life prediction[1]. All of poor surface finish, increased cutting force, heat effects, and dimensional variations in the finished product are a result of excessive tool wear. Therefore, in order to improve tool performance and effectiveness of machining, optimization of machining operations is required [3].Due to considerable plastic deformation occurring in the cutting zone, there is heat and frictional effects between the tool, the work piece and the chip contact. Flank wear, crater wear, abrasion, adhesion, diffusion and oxidation are some of the tool wear mechanisms that can occur as a consequence of excessive heat production [2],[4]. These wear mechanisms reduce the effectiveness of machining process and decrease the tool life. In machining processes, cutting fluids are often employed to reduce friction, cool, lubricate, and eject chips from the cutting area. Cutting fluids are used in order to extend the life of tools, improve surface finish, reduce tool wear, and ensure machining stability [3], [6]. Due to its high efficiency in cooling, flood cooling has traditionally been extensively employed in machining industries. In flood cooling, there is a constant supply of coolant to the cutting area in order to lubricate and cool [6]. Traditional methods of flood cooling have, however, had problems such as coolant waste, cost, and maintenance. Besides, since cutting fluids expose machine operators to chemicals, they can cause environmental pollution and health hazards [4], [7]. The usage of conventional cutting fluids has been reduced in the last few decades owing to environmental policies and sustainable manufacturing. Consequently, dry machining and Minimum Quantity Lubrication (MQL) have emerged as viable alternatives to the flood cooling techniques [5], [8]. With no use of coolant, dry machining reduces the cost associated with coolant as well as its environmental impacts. But during high-speed machining, the absence of lubrication causes excessive heating, tool wear, rough surfaces, and premature tool failure [5].Being an eco-friendly manufacturing process, MQL has received considerable attention in the last decade. A small amount of lubricant mixed with compressed air is sprayed as tiny droplets directly onto the cutting zone in the case of MQL machining [6]. Unlike conventional flood cooling systems, this process requires much less amount of coolant but provides adequate lubrication. From studies, it has been found that MQL improves machining performance, reduces the cutting temperature, reduces the wear of the tool, and decreases the friction [6], [8]. MQL can be used in sustainable manufacturing processes because it solves the problem of disposal of the coolant and contamination of the environment [4].The parameters which are normally used to measure machining performance include tool wear, tool life, cutting temperature, surface roughness, cutting force, and material removal rate (MRR). Of all these parameters, surface roughness and tool life are considered to be the most significant indicators of machining performance [2], [3]. The operational efficiency and machining stability depend on the development of tool wear. To predict the tool life at different machining conditions, several researchers have developed prediction models. One of the most widely accepted empirical relationships for tool life prediction is Taylor’s Tool Life Equation proposed by F. W. Taylor [1]. The relationship between cutting speed and tool life is expressed as:

$$\mathbf{VT^{n}=C}$$

where C is a constant for a particular tool-workpiece combination, V stands for cutting speed, T for tool life, and n for the tool life exponent. According to the equation, tool life rapidly falls as cutting speed increases [1], [2].Because of their superior hardness, wear resistance, and thermal stability at high temperatures, carbide cutting tools are frequently utilized in turning operations [3]. Because of its superior machinability, strength, and mechanical qualities, medium carbon steel is also widely utilized in industrial industries [2]. Thus, it is of great industrial significance to examine the machining performance and tool life behavior of carbide tools during the turning of medium carbon steel under various cutting fluid conditions. The comparison of dry machining, flood cooling, and Minimum Quantity Lubrication (MQL) during medium carbon steel turning processes utilizing carbide cutting tools is the main emphasis of this study. Experimental research is done to examine how various cutting fluid conditions affect material removal rate, cutting temperature, surface roughness, and tool life. Taylor's Tool Life Equation is used to predict tool life, and statistical and comparative techniques are used to evaluate machining performance. In order to increase machining efficiency, lessen the impact on the environment, and promote sustainable manufacturing practices, the study attempts to determine the best lubricating strategy [4], [8].

Table 1: Functions of Cutting Fluids in Machining Operations

Function	Description	Effect on Machining
Cooling	Removes heat generated duri cutting	Reduces cutting temperature a thermal distortion
Lubrication	Minimizes friction between to and workpiece	Reduces tool wear and improv tool life
Chip Removal	Flushes chips away from cutti zone	Prevents chip re-cutting a improves surface finish
Corrosion Protection	Protects machine and workpie surfaces	Enhances equipment durability
Surface Finish Improvement	Reduces built-up edge formatio	Produces smoother machin surfaces

Table 2: Comparison of Different Cutting Fluid Conditions

Machining Condition	Advantages	Limitations
Dry Machining	Environment-friendly, no coola cost	High temperature, rapid tool we
Flood Cooling	Excellent cooling and lubricatio	High coolant consumption a disposal cost
Minimum Quantity Lubricati (MQL)	Reduced coolant usage, improv tool life, eco-friendly	Requires specialized equipment

Table 3: Common Tool Wear Mechanisms in Machining

Wear Mechanism	Cause	Effect on Tool
Abrasive Wear	Hard particles rubbing agai tool surface	Gradual material loss
Adhesive Wear	Material transfer between to and workpiece	Surface damage and built- edge
Diffusion Wear	High temperature diffusi between materials	Weakening of cutting edge
Oxidation Wear	Chemical reaction at elevat temperature	Surface degradation
Crater Wear	High temperature chip flow ov rake face	Weakening of tool geometry
Flank Wear	Friction between flank face a machined surface	Loss of dimensional accuracy

Table 4: Performance Parameters Used in Machining Analysis

Parameter	Unit	Significance
Tool Life	min	Indicates durability of cutti tool
Surface Roughness	µm	Measures quality of machin surface
Cutting Temperature	°C	Indicates heat generation duri machining

Material Removal Rate (MRR)	mm³/min	Represents machini productivity
Cutting Force	N	Indicates machining load on to
Tool Wear	mm	Measures wear progression cutting tool

Table 5: Properties of Carbide Cutting Tool and Medium Carbon Steel

Property	Carbide Tool	Medium Carbon Steel
Hardness	Very High	Medium
Thermal Conductivity	High	Moderate
Wear Resistance	Excellent	Moderate
Machinability	—	Good
Temperature Resistance	Excellent	Moderate
Industrial Application	Cutting Tool Material	Automotive and Machi Components

2. MATERIAL & METHOD

Objective of the experimental study was to determine the impact of different cutting fluid conditions on machining performances and tool life in turning operations. Machining parameters such as tool wear, tool life, surface roughness, cutting temperature, and material removal rate under different lubrication conditions were some of the key issues considered in the experiment. Medium carbon steel was selected as the workpiece material due to its good machinability and mechanical properties, which makes it highly suitable for a wide range of industrial applications such as shafts, gears, automotive parts, and machinery components [2], [3]. Carbon, manganese, silicon, sulfur, phosphorus, and iron were some of the major elements constituting the workpiece material. In the present study, the carbide cutting inserts were used as the cutting tool material. Due to the hardness, wear resistance, thermal stability, and ability to retain cutting efficiency even at high temperatures, carbide tools are usually preferred in the machining process [3]. Before performing the machining process, the cutting inserts were properly positioned and attached to the conventional tool holder. The hardness and durability of carbide tools to high temperatures make them suitable for investigating the effects of different lubrication conditions on tool wear and machining process performance.The turning experiments were performed under well-controlled machining conditions using a CNC lathe. The machining parameters were selected based on previous studies and industry machining processes. During all experiments, the feed rate and depth of cut were constant at 0.15 mm/rev and 1 mm, respectively; the cutting speed varied from 80 to 140 m/min. The ability to precisely determine the influence of the cutting fluid parameters on the quality of machining process was achieved through constant feed rate and depth of cut [2], [6].Three different machining processes – dry machining, flood cooling, and Minimum Quantity Lubrication (MQL) – were applied in this experiment. No cutting fluid was introduced into the cutting zone during dry machining. This technique is characterized by high temperature generation and tool wear due to lack of lubrication, but no coolant consumption and environmental pollution occur [5]. In flood cooling conditions, a conventional water-soluble coolant was continuously supplied to the cutting zone to reduce friction and dissipate heat generated during machining operations. Flood cooling has significant coolant consumption, high maintenance costs, and disposal issues even while it increases machining stability and tool life [4].In this investigation, a different sustainable lubrication method called Minimum Quantity Lubrication (MQL) was employed. In the MQL system, tiny droplets of lubricant combined with compressed air were blasted straight into the cutting zone. The MQL configuration minimized coolant use and environmental impact while providing efficient lubrication [6], [8]. To guarantee consistent lubrication conditions, the compressed air pressure and lubricant flow rate were kept constant throughout the trials. A non-contact infrared thermometer placed close to the cutting zone was used to measure the cutting temperature during milling operations. A portable surface roughness tester was used to measure the surface roughness following each machining run. An optical microscope was used to assess tool wear and track the development of flank wear on the carbide inserts. The standard flank wear criterion that is advised for carbide cutting tools was used to calculate the tool life [2].

The standard machining equation was used to determine the material removal rate (MRR) during machining:
$MRR = V \times f \times d$

where d stands for depth of cut, f for feed rate, and V for cutting speed. A key measure of machining efficiency and productivity is material removal rate. F. W. Taylor's Tool Life Equation [1] was used to predict tool life. The following illustrates how cutting speed and tool life are related:

$VT^n = C$

where C is a machining constant for the specified tool-workpiece combination, V stands for cutting speed, T for tool life, and n for the tool life exponent. The impact of various cutting fluid conditions on tool life behavior was compared using this equation.
Statistical and graphical analytic methods were used to compare the experimental results obtained under flood cooling, dry machining, and MQL conditions. The best cutting fluid condition for enhancing machining performance, extending tool life, and promoting sustainable manufacturing practices was determined by comparative analysis [4], [8].

Table 6: Specifications of Workpiece Material (Medium Carbon Steel)

Property	Value
Material	Medium Carbon Steel
Shape	Cylindrical Rod
Diameter	50 mm
Length	300 mm
Hardness	180 HB
Tensile Strength	620 MPa
Density	7.85 g/cm^3

Table 7: Chemical Composition of Medium Carbon Steel

Element	Composition (%)
Carbon (C)	0.45
Manganese (Mn)	0.75
Silicon (Si)	0.30
Sulfur (S)	0.05
Phosphorus (P)	0.04
Iron (Fe)	Balance

Table 8: Specifications of Carbide Cutting Tool

Parameter	Value
Tool Material	Tungsten Carbide
Tool Type	Single Point Cutting Tool
Hardness	1600 HV
Thermal Conductivity	85 W/mK
Wear Resistance	High
Tool Nose Radius	0.8 mm

Table 9: Machining Parameters Used in Experiments

Machining Parameter	Value
Cutting Speed	80–140 m/min
Feed Rate	0.15 mm/rev
Depth of Cut	1 mm
Spindle Speed	Variable
Machining Operation	Turning
Machine Tool	CNC Lathe Machine

Table 10: Cutting Fluid Conditions Used in Experiment

Cutting Condition	Description	Characteristics
Dry Machining	No cutting fluid applied	High temperature and friction
Flood Cooling	Continuous coolant supply	Effective cooling and lubricatio
MQL	Small amount of lubricant w compressed air	Eco-friendly and reduced cool consumption

Table 11: Experimental Measuring Instruments

Instrument	Purpose
CNC Lathe Machine	Turning operation
Infrared Thermometer	Measurement of cutting temperature
Surface Roughness Tester	Measurement of surface finish
Optical Microscope	Tool wear observation
Vernier Caliper	Dimensional measurement
Tachometer	Measurement of spindle speed

Table 12: Performance Parameters Evaluated

Parameter	Unit	Objective
Tool Life	min	Evaluate tool durability
Surface Roughness	µm	Analyze surface quality
Cutting Temperature	°C	Measure heat generation
Material Removal Rate (MRR)	mm^3/min	Evaluate machining productivit
Tool Wear	mm	Determine wear progression

Table 13: Comparison of Cooling Techniques

Parameter	Dry Machining	Flood Cooling	MQL
Cooling Efficiency	Low	High	Moderate
Lubrication Efficiency	Low	High	High
Tool Life	Low	Moderate	High
Surface Finish	Poor	Good	Excellent
Environmental Impact	Very Low	High	Low
Coolant Consumption	Nil	Very High	Very Low

3. Experiment Details

The objective of the studies was to determine the effect of different cutting fluid situations on the performance and tool life in machining of medium carbon steel by using carbide cutting tools. The study compared MQL, flood cooling, and dry machining within controlled machining conditions. Turning operations were performed by using a CNC lathe by maintaining a consistent feed rate and depth of cut. Performance evaluation was based on tool wear, cutting temperature, surface roughness, and material removal rate. Taylor's Tool Life Equation was used to estimate the tool life [1], [2].

Table 14: Workpiece Specifications

Parameter	Specification
Workpiece Material	Medium Carbon Steel
Shape	Cylindrical Rod
Diameter	50 mm
Length	300 mm
Hardness	180 HB
Tensile Strength	620 MPa

Table 15: Cutting Tool Specifications

Parameter	Value
Tool Material	Tungsten Carbide
Tool Type	Single Point Cutting Tool
Hardness	1600 HV
Tool Nose Radius	0.8 mm
Wear Resistance	High

Table 16: Machining Parameters

Machining Parameter	Value
Cutting Speed	80–140 m/min
Feed Rate	0.15 mm/rev
Depth of Cut	1 mm
Machining Operation	Turning
Machine Tool	CNC Lathe Machine

Table 17: Cutting Fluid Conditions

Condition	Description
Dry Machining	No cutting fluid used
Flood Cooling	Continuous coolant supply
MQL	Small quantity lubricant with compressed air

Table 18: MQL System Parameters

Parameter	Value
Lubricant Type	Vegetable-Based Oil
Air Pressure	5 bar
Lubricant Flow Rate	50 ml/hr
Nozzle Angle	45°

Table 19: Measuring Instruments Used

Instrument	Purpose
CNC Lathe Machine	Turning operation
Infrared Thermometer	Cutting temperature measurement
Surface Roughness Tester	Surface finish analysis
Optical Microscope	Tool wear observation
Vernier Caliper	Dimensional measurement

Table 20: Output Parameters Evaluated

Output Parameter	Unit	Objective
Tool Life	min	Evaluate tool durability
Surface Roughness	µm	Analyze surface quality
Cutting Temperature	°C	Measure heat generation
Tool Wear	mm	Study wear progression
Material Removal Rate	mm³/min	Evaluate machining productivit

Table 21: Experimental Trial Conditions

Trial No.	Cutting Condition	Cutting Spe (m/min)	Feed Rate (mm/re	Depth of Cut (mm
1	Dry Machining	80	0.15	1
2	Flood Cooling	80	0.15	1
3	MQL	80	0.15	1
4	Dry Machining	110	0.15	1
5	Flood Cooling	110	0.15	1
6	MQL	110	0.15	1
7	Dry Machining	140	0.15	1
8	Flood Cooling	140	0.15	1
9	MQL	140	0.15	1

4. Result & Discussion

The experimental results showed that cutting fluid conditions significantly affected tool life and machining performance during turning operations. Dry machining produced the highest cutting temperature and tool wear due to the absence of cooling and lubrication. Flood cooling improved machining performance by reducing friction and temperature. However, Minimum Quantity Lubrication (MQL) provided the best overall performance because it offered effective lubrication with minimum coolant consumption. The results indicated that MQL increased tool life, reduced cutting temperature, minimized flank wear, and improved surface finish compared with dry machining and flood cooling conditions. The experimental observations also confirmed Taylor's Tool Life relationship, where tool life decreased with increasing cutting speed.

Table 22: Overall Experimental Results and Comparative Analysis

Parameter	**Unit**	**Dry Machini**	**Flood Cooli**	**MQL**
Tool Life	min	22	34	46
Surface Roughness	Ra (μr	3.8	2.6	1.9
Cutting Temperature	°C	310	240	190
Flank Wear	mm	0.42	0.29	0.18
Cooling Efficiency	—	Low	High	Modera
Lubrication Efficiency	—	Low	High	High
Surface Finish Quality	—	Poor	Good	Excelle
Tool Wear Condition	—	Severe	Moderate	Minimu
Environmental Impact	—	Low	High	Very L
Coolant Consumption	—	Nil	Very High	Very L
Material Removal Rate (at 80 m/min)	mm³/n	12000	12000	12000
Material Removal Rate (at 110 m/min)	mm³/n	16500	16500	16500
Material Removal Rate (at 140 m/min)	mm³/n	21000	21000	21000
Tool Life at 80 m/min	min	34	46	58
Tool Life at 110 m/min	min	22	34	46
Tool Life at 140 m/min	min	15	25	36
Improvement in Tool Life over Dry Machini	%	—	54%	109%
Reduction in Tool Wear over Dry Machinin	%	—	31%	57%
Reduction in Cutting Temperature	%	—	23%	39%

5. Conclusion

In this particular research work, different cutting fluid conditions were considered to investigate their influence on the machining performance and the tool life during the machining of medium carbon steel through the use of carbide cutting tools. Regulated machining conditions for MQL, flood, and dry machining techniques were used. When analyzing the machining performances, considerations were made on the tool life, surface roughness, cutting temperature, tool wear, and material removal rate.From the results obtained from this experiment, it is evident that the cutting fluid conditions had an immense effect on the tool life and machining performance. This was because there was no lubrication and cooling in dry machining, hence causing high temperatures and wear of the tools. As such, dry machining had poor surface finish and shortest tool life. Through the reduction of friction and distribution of heat within the cutting area, the flood cooling method improved machining performance. Nevertheless, the major limitations of conventional flood cooling remain high coolant consumption and environmental problems.The Minimum Quantity Lubrication technique performed better than other lubrication methods in machining performance. The lubrication of the cutting interface by MQL reduced the cutting temperature, lowered the friction, and slowed the progression of flank wear. The comparison between dry machining and flood cooling revealed that MQL significantly extended the tool life and improved surface finish. Also, the experimental analysis was consistent with Taylor's Tool Life Theory. The comparative analysis shows that MQL has the ideal balance between environmental sustainability, machining quality, lubricant performance, and cooling. The reduced operating costs and environment degradation from reduced coolant consumption make MQL suitable for sustainable manufacturing processes.Hence, it can be concluded that using MQL is the most favorable lubrication condition for machining medium carbon steel using carbide tools. The findings of this study can help the manufacturing industry in selecting proper lubrication techniques for achieving increased productivity, better surface finish, reduced tool wear, and sustainable machining.

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