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Performance Evaluation of Minimum Quantity Lubrication on EN3 Mild Steel Turning

Swapnil Rajan Jadhav, Ajay Vasantrao Kashikar

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***Abstract*—**Lubrication, cooling and chip removal are the desired functions of any cutting fluid. Conventional or flood lubrication requires high volume flow rate and cost associated with this is higher. In addition, flood lubrication possesses health risks to machine operator. To avoid these consequences, dry machining and minimum quantity are two alternatives. Dry machining cannot be a suited alternative as it can generate greater heat and poor surface finish. Here, turning work is carried out on a Lathe machine using EN3 Mild steel. Variable cutting speeds and depth of cuts are provided and corresponding temperatures and surface roughness values were recorded. Experimental results are analyzed by Minitab software. Regression analysis, main effect plot, and interaction plot conclusion are drawn by using ANOVA. There is a 95.83% reduction in the use of cutting fluid. MQL gives a 9.88% reduction in tool temperature, this will improve tool life. MQL produced a 17.64% improved surface finish. MQL appears to be an economical and environmentally compatible lubrication technique for sustainable manufacturing.

***Keywords*—**ANOVA, MQL, regression analysis, surface roughness.

I. Introduction

CUTTING fluid majorly contributes to the cost of production. "Also, cutting fluids are not environmentally safe, so stringent measures limit their adoption in machining. To conquer these challenges, near dry machining (NDM) is a promising technique in which a minimum quantity of metalworking fluid is sprayed in the metal cutting zone. Since minimal quantity lubrication is used, this process is known as MQL" [1]. Metalworking fluid is to provide lubrication, cooling, and effortless chip removal. The cost related to cutting fluids is between 7% to 17% of the total manufacturing cost. In flood lubrication volume flow rate of metalworking fluid is considerably higher i.e. 0.5 – 10 L/min" [2]. Alternatively, dry machining is not an optimal solution as heat is generated and surface roughness is higher. "MQL (Minimum quantity lubrication) possess volume flow rate of cutting fluid is comparatively low i.e. 0.05 – 0.5 L/hr" [2].

"To bring off lower cutting temperature and higher machining efficiency environmentally, minimum quantity lubrication (MQL) as a green technology is extensively adopted in metal cutting process" [3]. "Minimal Quantity Lubrication, Near-Dry Machining or NDM, Micro-Lubrication or Microlubrification, Micro-Dosing are sometimes referred to as MQL" [4]. In MQL minute quantity of cutting fluid is supplied to the metal cutting zone in the form of droplets or as a blend with compressed air, forming a mist. "This encourages decreased induced thermal shock and helps to maximize the workpiece surface integrity in situations of high tool pressure" [5].

"MQL machining has been divided into two methods based on the methods used for supplying metal cutting fluid to the metal cutting zone. The first method is supplying metal cutting fluid spray or mist by an external nozzle. The second method is supplying metal cutting fluid spray or mist by an internal nozzle. In this method, metal cutting fluid mist is supplied through a metal cutting tool, such as that used in high-pressure lubrication" [6]. "The concept of minimum quantity lubrication (MQL) may be considered as a rigorous solution in achieving reduced tool wear and improved surface finish while maintaining cutting forces or power at reasonable levels, if the MQL system can be properly designed" [7]. "It has been found that MQL is possible to maintain or improve reasonable tool life and surface quality" [10]. "The lubricant is either applied from outside as an aerosol using compressed air or it is shot at the tool in the form of droplets. Another possibility is internal lubricant feed through the rotating machine tool spindle and the inner channels of the tool" [11].

II. Problem Definition

In flood lubrication, "considering the extensive volume of metal cutting fluid is important, often the used fluid is filtered, cooled down and re-used. This process is imitated for an extended period past disposal of the cutting fluid. Further, the overall cost of machining escalates due to additional costs for the high volume of expensive metal cutting fluid. Expenses of filtration are also not negligible. Flood lubrication affects visibility at the machining zone" [5]. "Visibility is essential during the metal cutting process without any hazards" [5].

Flood lubrication leads to corrode the cutting tool at an accelerated rate, and therefore adequate insulation on the significant parts is extremely desired. "Considering cost and the stricter environmental laws are enforced, alternatives have been sought to minimize the use of cutting fluid in machining operations. Some of these are dry machining and machining with Minimum Quantity Lubrication (MQL)" [8]. "The machining temperature at the cutting zone is an important index of machinability and needs to be controlled as far as possible. MQL is expected to provide some favorable effects mainly through reduction in cutting temperature." [9].

Swapnil Rajan Jadhav is with Lokmanya Tilak College of Engineering, India (corresponding author; e-mail: swapniljadhav034@gmail.com).

Ajay Vasantrao Kashikar is with Lokmanya Tilak College of Engineering, India (e-mail: ajaykashikar1@gmail.com).

III. METHODOLOGY

For experimentation, Super Side Production Rajkot, Gujarat (India) ALPHA make Lathe machine is used. Bed length: 1050 mm, bed width: 241 mm, center Height: 165 mm, spindle bore: 37 mm.

A. Workpiece

Ø 20 MM EN3 mild steel is selected for experimentation.

B. Chemical Composition Test

Chemical composition test is conducted on Optical Emission Spectrometer, 32 Channel, 8 bases, Make Fisons Instrument as shown in Fig. 1.

Fig. 1 Spectrometer setup for chemical composition test

The results obtained from the chemical composition test on the spectrometer are given in Table I.

TABLE I
CHEMICAL COMPOSITION OF EN3 MILD STEEL

Carbon (C)	Sulfur (S)	Phosphorus (P)	Silicon (Si)
0.2339	0.0399	0.0602	0.2143
Manganese (Mn)	Nickel (Ni)	Chromium (Cr)	Molybdenum (Mo)
0.5804	0.0551	0.1174	0.0219
Vanadium (V)	Copper (Cu)	Tungsten (W)	Titanium (Ti)
0.0029	0.0985	0.0011	0.0009
Arsenic (As)	Tin (Sn)	Cobalt (Co)	Aluminum (Al)
0.0019	0.0072	0.0025	0.0027
Lead (Pb)	Boron (B)	Niobium (Nb)	Zinc (Zn)
-0.0017	0.0003	-0.0025	0.0022

C. Machining Parameters

TABLE II
INPUT PARAMETERS

Parameters	Values
Cutting speed	240, 375, 570 (rpm)
Depth of cut	0.5, 1, 2 (mm)
Environment	Flood, MQL

Cutting speed (rpm), depth of cut (mm) and lubrication environment will be three input parameters are shown in Table II during turning operation.

Cutting tool temperature (° C) and surface roughness (µm) will be observed as output parameters.

D. Experimental Procedure

1) Mount EN3 Mild steel workpiece on lathe machine.
2) Adjust cutting speed (rpm).
3) Select depth of cut (mm).
4) Adjust the cutting fluid flow as required.
5) Start the pressurized air to flow through the MQL applicator.
6) Start machining.
7) Note down the temperature by infrared temperature gun.
8) Unmount EN3 turned workpiece and measure the surface roughness.
9) Repeat the above procedure for flood-type lubrication machining. This setup can be seen in Fig. 2.

Fig. 2 Experimental set up for EN3 turning

E. MQL Applicator

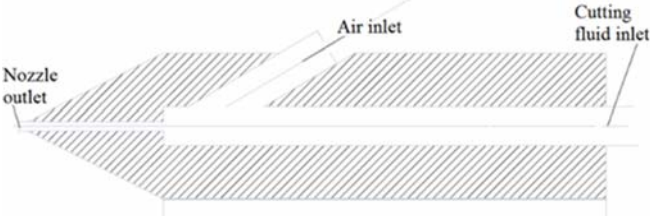

Fig. 3 MQL applicator CAD representation

MQL applicator is fabricated in the machine shop. For this purpose, mild steel round bar of 120 mm long and Ø 30 mm in diameter is taken. As depicted in Fig. 3 turning and drilling operations are carried out.

For optimized parameters of the MQL applicator, Taguchi's 3 levels orthogonal array method is adopted.

TABLE III
CONTROL FACTORS FOR TAGUCHI'S 3 LEVEL ORTHOGONAL ARRAY

Nozzle outlet diameter (mm)	Cutting fluid inlet diameter (mm)	Air inlet angle	Air pressure (bar)
1	5	30°	3
2	8	60°	4
3	10	45°	5

Minitab software is used to conduct Taguchi's design of experiments. The results obtained from 3 levels orthogonal array are given in Table IV.

TABLE IV
TAGUCHI'S DOE FOR MQL APPLICATOR

Nozzle outlet diameter (mm)	Cutting fluid inlet diameter (mm)	Air inlet angle	Air pressure (bar)
1	5	30º	3
1	8	60º	4
1	10	45º	5
2	5	60º	5
2	8	45º	3
2	10	30º	4
3	5	45º	4
3	8	30º	5
3	10	60º	3

Based on results obtained by Taguchi's orthogonal array, the experiments are conducted to record the minimum cutting fluid volume flow rate shown in Table V.

TABLE V
RESUTLS OF TAGUCHI'S DOE FOR MQL APPLICATOR

Nozzle outlet diameter (mm)	Cutting fluid inlet diameter (mm)	Air inlet angle	Air pressure (bar)	Cutting fluid volume flow rate (L/hr)
1	5	30º	3	0.55
1	8	60º	4	0.73
1	10	45º	5	0.82
2	5	60º	5	1
2	8	45º	3	1.25
2	10	30º	4	1.31
3	5	45º	4	1.22
3	8	30º	5	0.9
3	10	60º	3	0.88

After successful completion of experiments, the results are analyzed by Taguchi analysis in MINITAB software. The analysis is a relation between Cutting fluid volume flow rate for MQL applicator versus Nozzle outlet diameter (mm), Cutting fluid inlet diameter (mm), Air inlet angle, Air pressure (bar), and Cutting fluid volume flow rate (L/hr).

The main effects plot is obtained from the Taguchi analysis shown in Fig. 4 and the result gives us the best-optimized design parameters to get minimum cutting fluid volume flow rate at the machining zone.

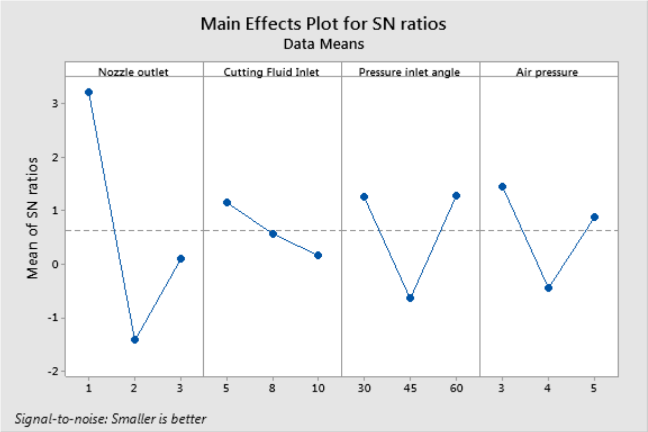

Fig. 4 Main effect plot for SN ratios

From the above Main effects plot for SN ratio, it is clear that the following design parameters are the optimal solution for the MQL applicator fabrication and its design.

TABLE VI
OPTIMIZED DESIGN PARAMETERS MQL APPLICATOR

Parameters	Values
Nozzle outlet diameter (mm)	2
Cutting fluid inlet diameter (mm)	10
Air inlet angle	45º
Air pressure (bar)	4

Cutting fluid flow rate at 1.25 L/hr and air pressure is at 4 bar is maintained in the MQL applicator throughout the experimentation. MQL spray is obtained at the machining zone.

IV. RESULT ANALYSIS

After successful experimentation, respective cutting temperatures and surface roughness values are recorded and results analyzed by Minitab software.

A. Relationship between Cutting Tool Temperature and Input Parameters

A linear relationship on variation in cutting temperature during turning is plotted using the Main effects plot in MINITAB software as shown in Fig. 5. It is observed that the depth of cut has a higher contribution to the variability of cutting temperature over the other experimental factors. Considerably, there is a reduction in cutting temperature during MQL turning.

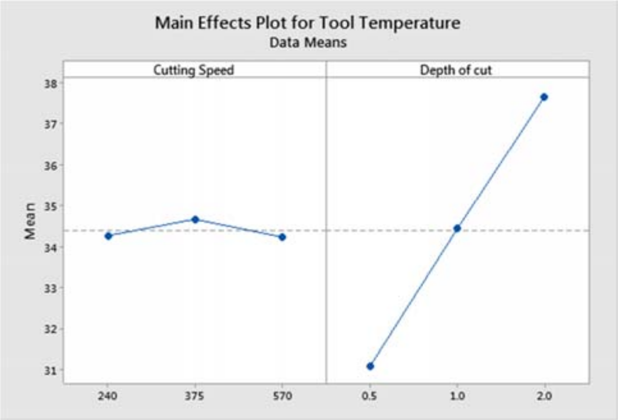

Fig. 5 Main effect plot for cutting tool temperature

For a general linear model of ANOVA, It is observed in Table VII that the depth of cut is the most significant parameter. The F-value for the depth of cut is 120.83 ($p<0.0001$). In MQL machining, air at high pressure of 4 bar is mixed with minimum cutting fluid. "Mixing of air in cutting fluid reduces the cutting temperature. Both convective and evaporative heat transfer results in lowering of cutting temperature" [5].

TABLE VII
ANALYSIS OF VARIANCE FOR CUTTING TOOL TEMPERATURE

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	2	62.734	31.3672	60.43	0
Cutting Speed	1	0.0104	0.0104	0.02	0.892
Depth of cut	1	62.724	62.7239	120.83	0
Error	6	3.1146	0.5191	-	-
Total	8	65.849	-	-	-

To demonstrate the conformity of the experimental results regression analysis is performed using Minitab software.

1) The Regression Equation for Cutting Tool Temperature

$$\text{Cutting tool temperature} = 29.549 - 0.00025 * \text{Cutting Speed} + 4.233 * \text{Depth of cut} \quad (1)$$

E.g. cutting speed=240 rpm and depth of cut= 1 mm.
So,

$$\text{Cutting tool temperature} = 29.549 - 0.00025 * 240 + 4.233 * 1$$

$$\text{Cutting tool temperature} = 33.722\ {}^{\circ}C$$

From (1) we have obtained the theoretical value of tool temperature and practical value of tool temperature when cutting speed is 240 rpm and depth of cut is 1 mm is 34.2 °C Experimental and analytical values are nearly equal with the error of 1.41 %. Hence, the results are valid.

B. Relationship between Surface Roughness and Input Parameters

The main effect plot of Ra values for surface roughness is plotted against cutting speed and depth of cut as shown in Fig. 6.

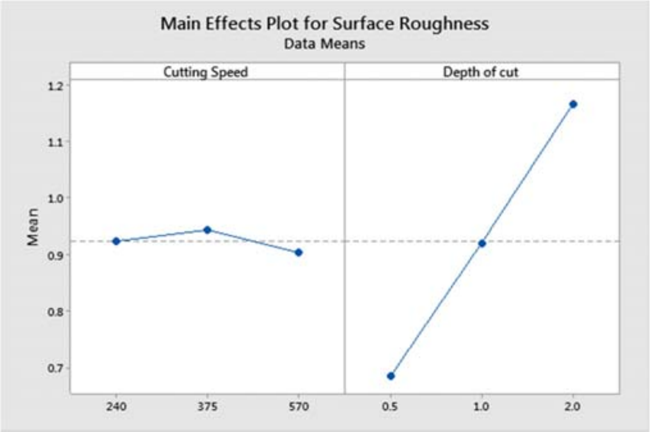

Fig. 6 Main effect plot for surface roughness

It is observed from Fig. 6 that when cutting speed changes from 240 to 375 rpm, there is an increase in roughness but when speed changes from 375 to 570 rpm, there is a decrease in roughness value. Hence, the Ra value is not proportionate with cutting speed. However, the depth of the cut is directly proportional to the Ra value.

For a general linear model of ANOVA, It is observed in Table VIII that the F-value for depth of cut is 34.93, which is maximum. Hence, it is the most significant parameter. Surface finish depends upon the feed rate of the tool for workpiece and supply of cutting fluid. As the depth of cut increases, poor surface finish occurs.

TABLE VIII
ANALYSIS OF VARIANCE FOR SURFACE ROUGHNESS

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	2	0.34029	0.17014	17.51	0.003
Cutting Speed	1	0.00083	0.00083	0.09	0.78
Depth of cut	1	0.33946	0.33946	34.93	0.001
Error	6	0.05831	0.00972	-	-
Total	8	0.3986	-	-	-

To demonstrate the fitness of the experimental measurement regression analysis is performed using Minitab software.

2) Regression Equation for Surface Roughness

$$\text{Surface roughness} = 0.588 - 0.000071 * \text{Cutting Speed} + 0.3114 * \text{Depth of cut} \quad (2)$$

E.g. cutting speed=570 rpm and depth of cut= 2 mm.
So,

$$\text{Surface roughness} = 0.588 - 0.000071 * 570 + 0.3114 * 2$$

$$\text{Surface roughness} = 1.1709\ \mu m$$

Equation (2) gives an analytical value of surface roughness (Ra). The practical value is 1.2µm. The experimental and practical values are nearly equal with an error of 2.54%. Hence, these results are also valid.

C. Comparative Analysis

TABLE IX
COMPARISON BETWEEN FLOOD AND MQL TURNING

	Flood	MQL	Difference	% Change
Surface Roughness (µm)	1.1211	0.9233	0.1978	17.64
Cutting tool temperature (°C)	38.15	34.38	3.77	9.88
Volume flow rate (L/hr)	30	1.25	28.75	95.83

Table IX clearly shows that the average tool temperature in flood-type machining is 38.15 °C and in MQL is 34.38 °C. There is a 9.88 % reduction in temperature. The average Ra value in flood type machining is 1.1211 µm and in MQL is 0.9233 µm. There is a 17.64% improvement in surface finish. In flood type, the machining flow rate is 30L/hr. In addition, in MQL which is 1.25 l/hr. There is a substantial reduction of up to 95.83% in the use of cutting fluid.

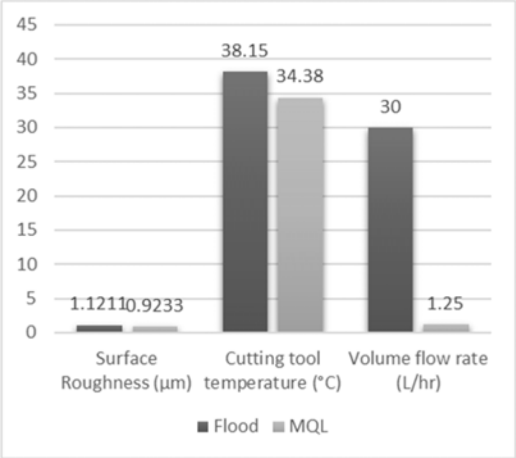

Fig. 7 Graphical representation for comparison between flood and MQL turning

Fig. 7 shows comparative analysis. This huge reduction in the use of cutting fluid will reflect in the cost of procurement, cost of storage, and mainly cost of disposal. Hence, the cost of production will be minimized with the use of only 4.17% of cutting fluid.

V. CONCLUSION

Work is carried out on a Lathe machine on material EN3 mild steel. In addition, different parameters are analyzed. Results show that the MQL system is much better than the conventional machining. Reduction in cutting temperature and improved surface finish is observed in MQL.

1) There is a 95.83 % reduction in the use of cutting fluid.
2) MQL gives a 9.88 % reduction in tool temperature. This will improve the tool life.
3) Surface finish in turning of EN3 is better in MQL. It gives a 17.64 % improvement in surface finish
4) ANOVA concludes that depth of cut is the most significant factor in turning operation.

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