International Journal of Research in Management, Science & Technology (E-ISSN: 2321-3264)
Vol. 5, No. 3, December 17
Available at www.ijrmst.org

Influence of Cutting Fluid Condition on Material Removal Rate and Surface Finish in Straight Turning Process of En31 steel on CNC Lathe

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Abstract— **Turning is one of the machining processes, widely used in industries during the manufacturing or machining of products. As the population is growing day by day, their demand of different articles may be decorative, household, etc., is increasing day by day and also on time. Thus, it is getting necessary for the industries to develop their manufacturing as well as machining process to sustain in the competition.**

Increasing machining rate, will consequently lead to the high values of cutting parameters such as cutting velocity, feed rate, material removal rate, etc. This directly results in high temperature generation during the machining process. The high temperature creates high temperature zones both on workpiece and tool material which will directly affect their life. In order to increase the life of tool material and maintaining the surface finish of the workpiece, specialized cooling/lubricant techniques should be used. One of the processes is Minimal Quantity Lubrication process, which not only reduces the quantity of lubricant introducing on the tool chip interface but also ensures proper cooling by allowing the mist form of the lubricant at tool chip interface.

The present paper deals with the effect of cutting fluid condition and cutting parameter on material removal rate and surface finish in turning process of En31 steel using MQL setup on CNC lathe machine. The experiment is carried out under 3 different cutting environments namely dry, flood and MQL with the help of taguchi method and its effect on material removal rate and surface finish is being observed.

***Keywords*—MQL, EN-31, Material Removal Rate, cutting fluid, Metal cutting, Machining, Carbide Cutting Tool, Wet Machining, Taguchi method.**

I. INTRODUCTION

Manufacturing can be described as transformation of raw material in some goods for the human satisfaction. In manufacturing process, the initial stage is product design and product delivery are the final stage. It alters the form, shape and size of workpiece material to the product we required. There are various processes in manufacturing process such as casting, coating, moulding, forming, machining, joining, etc. But manufacturing process is basically classified into forming process, deforming process, material removing process or machining process, joining process and material properties modification process.

In manufacturing industry, machining process is widely used. It also consists of various subtypes, such as milling, drilling, turning, boring, grooving, etc. out of which turning is still most important operation. Turning process is the machining process in which the tools axes of movement is a straight line and remains horizontal. In turning operation higher values of cutting parameters will increase the production rate but at the cost of surface quality of product and tool life. As during machining operation, higher values of cutting parameters leads to the generation of high temperature zones at the tool work interface leading to the deterioration of workpiece and also decrease in life of the tool. Tool damage can occur in 3 ways i.e., adhesion, thermal softening, mechanical chipping.

Surface finish is also one of the major parameter on which the accuracy and perfection of the operation can be judged. Good surface finish is required to prevent the premature fatigue failure, wear and noise and for improvement of workpiece life. In order to reduce the temperature and to increase tool as well as workpiece life, conventionally cutting fluids were used. They play the role of cooling down the temperature zones at tool chip interface and also flush the chips form during the operation resulting in decrease in coefficient of friction at tool chip interface as compared to dry machining.

As each advantage has a disadvantage too, conventional used of cutting fluids were found to be hazardous for humans as well as environment resulting in skin infections followed by various types of diseases. It is estimated that the cost of cutting fluid is 7%-17% range of total cost in industry. Thus, increased rate of cutting fluid will adversely affect the working capital of the industry. Thus, an alternative is needed for which can serve the purpose of cutting fluid applied in flooded condition.

The various cooling techniques are available such as flood cooling, solid lubricant, high pressure cooling, cryogenic cooling and minimum quantity lubrication each having some advantage as well as disadvantage too. Flood machining is technique in which cutting fluid is used in enormous quantity. This has advantages of low temperature generation, better surface finish and less tool wear. But the major disadvantage behind using such technique is cost of cutting fluid, disposal and environment problems as well as health hazards caused due to it. Application of lubricant in solid form is solid lubrication. It delivers efficient boundary lubrication, improving friction and minimizing wear in extreme operation environment results in high temperature stability and high load carrying capacity with disadvantages such as poor heat dissipation properties, poor self-healing properties. High pressure cooling is an emerging technique that delivers high pressured fluid to the tool and machined material resulting in better penetration of cutting fluid in tool chip interface and proper cooling can be ensured. The only disadvantage of this technique is that it is expensive . Cryogenic cooling is a cooling technique where cutting fluid are replaced by cryogenics such as liquid nitrogen which at -196˚C is applied to the cutting zone for cooling purpose. Also, there is no issue of cutting fluid disposal in this as liquid nitrogen can be harmlessly vaporized in atmosphere. But the case is not so in utilization of each cryogenics as utilization solid CO_2 leads to certain environmental problems.

II. MINIMUM QUANTITY LUBRICATION

Minimum Quantity Lubrication also termed as semi dry lubrication or micro lubrication is a technique suggesting usage of cutting fluid in the range of 50-300 ml per hour. MQL combines functionality of cooling lubrication technique with the consumption of extremely less amount of cutting fluid. There are 3 types of MQL technique. First one is Low pressure spray systems: These systems have the flow rate around 0.5 to 10 l/hr. In this cooling technique, lubricant is transmitted to the machining surface by drawing it in air current. Another system uses dosing pumps delivering defined quantity of cooling lubricant to the machining surface without air. The flow rates are adjusted to 0.1 to 10 ml/cycle with up to 260 cycle/min. The third and most widely used pressure systems includes transportation of lubricant to the nozzle by pump through the spate supply pipe where it is mixed with compressed air at certain pressure resulting in formation of mist form of lubricant. The flow rates here are about 50-300 ml/hr. In this one can adjust the quantities of air and lubricant separately.

III. SCOPE

Up till now in the field of turning using MQL working research is limited up to the effect of implementation of the MQL system in turning operation with the consideration of parameters such as surface roughness, surface integrity, dimensional deviation, tool wear. The experiments carried out up till now were just compared the results of parameters under various cooling environments to show that MQL gives best result. It plays a major role regarding the factors of reducing machining cost and other problems arises due to utilization of cutting fluids. Thus, the benefits of this system will prove to be beneficial for an industry if the concept is properly commercialized.

Another region where negligible amount of work is done is on the evaluation of temperatures between tool and chip interface after machining, metallurgical investigation of tool and workpiece after machining. It should be noted that after machining, the tool and workpiece should retain their original properties on the basis of which they were selected for machining as if the properties of tool and workpiece will change after machining then they will be of no use.

IV. WORKING PRINCIPLE

High cutting zone temperature is generally tried to be controlled by employing flood cooling by soluble oil. In high speed–feed machining, conventional cutting fluid application fails to penetrate the chip-tool interface and thus cannot remove heat effectively and the use of cutting fluid has become more problematic in terms of both employee health and environmental pollution. Addition of extreme pressure additives in the cutting fluids does not ensure penetration of coolant at the chip–tool interface to provide lubrication and cooling. Minimum quantity lubrication (MQL) is based on the principle that a drop of liquid is split by an air flow, distributed in streaks and transported in the direction of flow of air. MQL consists of a mixture of pressurized air and oil micro-droplets applied directly into the interface between the tool and chips. MQL decreased the contact length compared to dry cutting for both short and long engagement time. However, high-pressure jet of lubricant, when applied at the chip–tool interface, could reduce cutting temperature and improve tool life to some extent. The schematic diagram of MQL working principal is shown below:

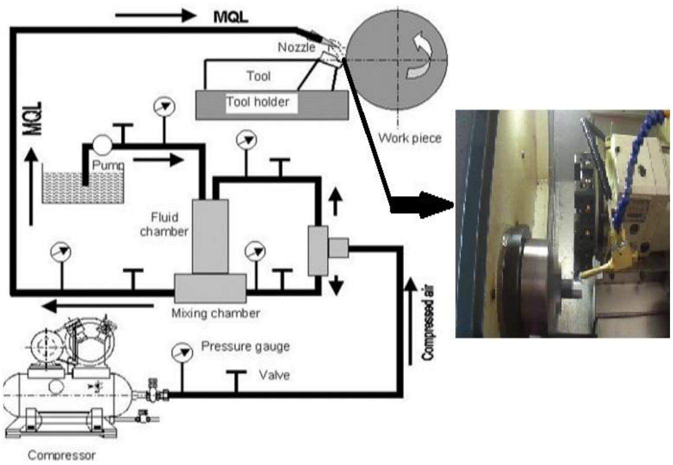

Fig. 1: Diagram of Working of MQL

In the mixing chamber of the setup, compressed air at about pressure 5bar is the inlet of the mixing chamber where lubricant is admitted due to creation of vacuum by admission of high pressure gas. An air ejector in the mixing chamber plays a vital role as it atomizes the mixture of air and lubricant into fine mist form known as aerosol. This aerosol is directly introduced at tool chip interface out of the mixing chamber through the nozzle. Minimum Quantity Lubrication also termed as semi dry lubrication or micro lubrication is a technique suggesting usage of cutting fluid in the range of 50-300 ml per hour. MQL combines functionality of cooling lubrication technique with the consumption of extremely less amount of cutting fluid. There are 3 types of MQL technique. First one is Low pressure spray systems: These systems have the flow rate around 0.5 to 10 l/hr. In this cooling, lubricant is transmitted to the machining surface by drawing it in air current. Another system uses dosing pumps delivering defined quantity of cooling lubricant to the machining surface without air. The flow rates are adjusted to 0.1 to 10 ml/cycle with up to 260 cycle/min. The third and most widely used pressure systems includes transportation of lubricant to the nozzle by pump through the spate supply pipe where it is mixed with compressed air at certain pressure resulting in formation of mist form of lubricant. The flow rates here are about 50-300 ml/hr. In this one can adjust the quantities of air and lubricant separately.

V. CUTTING FLUID

In order to reduce the effects of high temperature zone at tool chip interface, cutting fluids are used during machining process. The use of the cutting fluids results in heat/high temperature zone elimination, chip removal and lubrication at too chip interface. But recent study reveals that cutting fluid has several disadvantages too such as it can have caused environmental as well as health hazards. Also, the problem of disposal of cutting fluid arises specially in flood machining condition. The cutting fluid cost about 7-17% of the total machining cost. Hence, the fact must take into consideration. Therefore, it is essential to reduce this cost to save both money and work environment.

The Panamol HM Lubricant is used as a cutting fluid in this experiment having flash point at 180℃, viscosity at 40℃ as 32 Ns/m^2 along with viscosity index as 95. The Lubricants are manufactured from selected base oil which changes less in terms of viscosity with temperature. These oils are fortified with additives to offer long services, however during their selection care must be taken to ensure none clogging of sintered bush bearing.

VI. TAGUCHI METHOD

Taguchi develop a special design of orthogonal array to study the entire parameters with small number of experiment only. Taguchi method is used for design of high quality system. It optimizes the performance characteristics by setting down of design parameters and reducing sensitivity of system performance to variation source. The optimization of parameter is to be done in 3 steps, i.e., system design, parameter as well as tolerance design.

- In system design, in order to produce a functional design, engineer has to apply scientific and engineering knowledge. It involves design of process and product.
- In parameter design, the process parameter values are optimized for improving quality characteristics and to identify product parameter value under optimum process parameter values.
- Tolerance design is a method to fine tune the parameter design results by tightening the factors tolerances having the significant influence on products. Thus, this identifies the need of innovation and better materials, parts, machinery, etc.

In case of parameter design for Taguchi method, following steps are involved:

1. Identification of quality characteristics and selecting design parameters.
2. Determining no. of levels for design parameters
3. Selection of a proper orthogonal array and assignment of design parameters to orthogonal array
4. Carrying out experiments based on orthogonal array
5. Analysis of experimental results using S/N ratio
6. Selection of optimal level of design parameters
7. Verification through confirmation experiment.

Taguchi Method recommends using signal-to-noise ratio, where signal is the required entity and noise is unnecessary entity. There are 3 modules of quality characteristics in analysis of S/N ratio: Lower the better, Higher the better and Nominal the best. The optimal level of process parameters is levelled with greatest S/N ratio.
Formulas for calculation of S/N ratio are:

Nominal is the best: $S/N_T = 10 \log(\bar{y} / S_y{}^2)$

Larger is the best (max.): $S/N_L = -10 \log (1/n\sum_{i=1}^{n} 1/y_i{}^2)$

Smaller is best (min.): $S/N_S = -10 \log (1/n\sum_{i=1}^{n} y_i{}^2)$

Where, $\bar{y}$ = Average of observed data,
$S_y{}^2$ = Variance of y,
n = No. of observations
y = Observed data

The S/N ratio is to be calculated in decibel units. Here, larger is the better modules are selected, as the desired output parameter of a machining process of larger material removal rate and good surface finish.

VII. METHODOLOGY

The experiment is carried out by turning En31 steel of 25mm dia. and 100 mm length on a CNC lathe machine under different cutting environments namely dry, flood and MQL, using various cutting speed-feed combinations. The cutting parameters selected are cutting speed, depth of cut and feed rate. The composition of En31material is tested by using spectrometer. The experiment is carried out on a basis of L9 orthogonal array which suggests that, total 9 experiments were to be carried out per cutting environment.

L9 orthogonal array have following benefits:

1. Conclusions valid over the entire region spanned by thecontrol factors and their settings.
2. Large saving in the experimental effort.
3. Analysis is easy

The cutting tool used in this research is CVD coated carbide TiC+AI2O3+TiN insert. The type of inserts is DNMG 110408E-TM.

The process parameters selected are as follows: The initial cutting parameters are: cutting speed = 130 m/min, feed rate 0.2 mm/rev. and depth of cut = 0.1 mm. the range of cutting speed are defined by varying it in range of 130-190 m/min and feed rate range of 0.2-0.5 mm/rev. with depth of cut of 0.1mm

TABLE I
PROCESS PARAMETERS

Factor	**Code**	**Level 1**	**Level 2**	**Level 3**	**Unit**
Cutting Speed	A	130	160	190	m/min
Feed	B	0.2	0.3	0.4	mm/rev.
Depth of Cut	C	0.1	0.15	0.2	mm

TABLE II
EXPERIMENTAL CONDITION

Machine Tool	CNC Lathe Machine, Fanuc Oi Mate-TD
Work specimen Material Size	En31 steel (C 1.021%, Si 0.260%, Mn 0.497%, P 0.040%, S 0.042%, Cr 1.215%, Ni 0.072%, Mo 0.028%, Al 0.018%, Cu 0.043%, V 0.009%, Nb 0.011%, Ti 0.005%) 25mm diameter and 100mm length
Cutting tool (insert) Other Specifications Tool Holder	Carbide, DNMG110408E-TM IC dia. 9.525mm, Thickness 4.76mm, Hole dia. 3.81mm, Corner Radius 0.8mm. PDJNR1616 H11 BIX
Output Parameters	MRR, Surface Finish and Type of Chip Generated
MQL Supply	Air 5 bar, Lubrication through External Nozzle
Environment	Dry, Flood Machining, MQL

The L9 OA is repeated for dry, flood and MQL. The sample data obtained for MRR and surface roughness under different environmental condition is shown below

TABLE III
EXPERIMENTAL RESULTS FOR MACHINING UNDER DRY CONDITION

Exp. No.	**Cutting Speed**	**Feed**	**Depth of cut**	**Surface Roughness (in µm)**	**MRR**
1.	1	1	1	1.97	1949.95
2.	1	2	2	1.95	3326.4
3.	1	3	3	1.90	5083.02
4.	2	1	2	3.42	4299.46
5.	2	2	3	3.53	6197.11
6.	2	3	1	3.2	6197.11
7.	3	1	3	4.28	7603.18
8.	3	2	1	4.19	5679
9.	3	3	2	5.47	10341.4

TABLE IV
EXPERIMENTAL RESULTS FOR MACHINING UNDER FLOOD CONDITION

Exp. No.	**Cutting Speed**	**Feed**	**Depth of cut**	**Surface Roughness (in µm)**	**MRR**
1.	1	1	1	1.77	2331.9
2.	1	2	2	1.72	1824.15
3.	1	3	3	1.89	5140.8
4.	2	1	2	2.46	4271.85
5.	2	2	3	3.73	6545
6.	2	3	1	3.23	6545
7.	3	1	3	4.09	4938.75
8.	3	2	1	4.17	6617.75
9.	3	3	2	5.68	3936.21

TABLE V
EXPERIMENTAL RESULTS FOR MACHINING UNDER MQL CONDITION

Exp. No.	**Cutting Speed**	**Feed**	**Depth of cut**	**Surface Roughness (in µm)**	**MRR**
1.	1	1	1	1.59	2019.59
2.	1	2	2	1.46	3534.291
3.	1	3	3	1.76	5697.6

4.	2	1	2	2.29	4588.127
5.	2	2	3	3.05	7180.8
6.	2	3	1	3	7180.8
7.	3	1	3	3.8	8568
8.	3	2	1	3.82	6499.84
9.	3	3	2	4.67	12161

VIII. ANALYSIS OF DATA

A. Material Removal Rate

The material removal rate is the volume of material removed per unit time in mm^3/sec.

Material Removal Rate MRR = $\frac{\frac{\pi}{4}\times[{D_1}^2-{D_2}^2]\times L}{t}$ mm^3/min.

Where, D_1=dia. of workpiece before turning (in mm.) =25mm
D_2=dia. of workpiece after turning (in mm.) =23mm
L=length of turning (in mm.) =30mm
t=Machining Time (in min.)

Analytically, The MRR is calculated by using above formulae for each combination of L9 OA. Three different cutting parameters are available and in order to achieve reliable results from the statistical analysis, three repeated tests are conducted for each trial. Therefore, total 9 experiments are carried out using L9 OA.

Taguchi suggests the transformation of the repetition data in a trial into a consolidated single value called the S/N ratio. In the Taguchi method, the term ‘signal’ represents the desirable value (mean) for the output characteristic and the term ‘noise’ represents the undesirable value (S.D.) for the output characteristic.So, the S/N ratio represents the amount of variation present in the quality characteristic.Thus S/N ratio is the measure of deviation of quality characteristic from the desired value in decibels. The response table as well as response graph for Signal to noise ratio from Taguchi analysis is generated for MRR.The greater S/N ratio corresponds to smaller variance of output characteristics around the desired value. The larger the better module is selected as larger will be the material removal rate, larger will be the production rate and hence, production efficiency increases.

TABLE VI
EXPERIMENTAL RESULTS FOR MRR AND S/N RATIO IN DRY MACHINING

Exp. No.	Cutting Speed	Feed	Depth of cut	MRR	SNRA1 (in dB)
1.	1	1	1	1949.95	65.8005
2.	1	2	2	3326.4	70.4395
3.	1	3	3	5083.02	74.1224
4.	2	1	2	4299.46	72.6683
5.	2	2	3	6197.11	75.8438
6.	2	3	1	6197.11	75.8438
7.	3	1	3	7603.18	77.6199
8.	3	2	1	5679	75.0854
9.	3	3	2	10341.4	80.2916

TABLE VII
RESPONSE TABLE FOR S/N RATIO IN DRY MACHINING

Level	Cutting Speed	Feed Rate	Depth of Cut
1	70.12	72.03	72.24
2	74.79	73.79	74.47
3	77.67	76.75	75.86
Delta	7.54	4.72	3.42
Rank	1	2	3

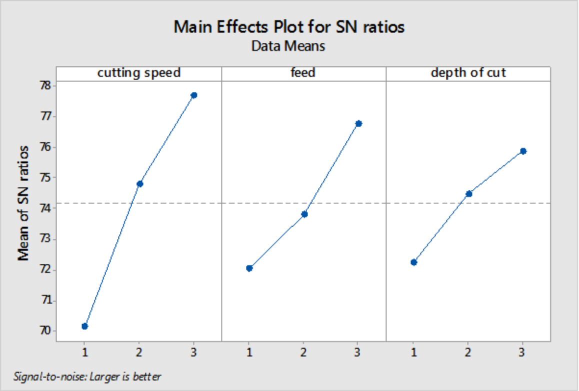

Fig. 2: Mean Signal to Noise Graph for MRR in Dry Condition

TABLE VIII
EXPERIMENTAL RESULTS FOR MRR AND S/N RATIO IN FLOOD MACHINING

Exp. No.	Cutting Speed	Feed	Depth of cut	MRR	SNR A1 (in dB)
1.	1	1	1	2331.9	67.3542
2.	1	2	2	1824.15	65.2212
3.	1	3	3	5140.8	74.2206
4.	2	1	2	4271.85	72.6123
5.	2	2	3	6545	76.3182
6.	2	3	1	6545	76.3182
7.	3	1	3	4938.75	73.8723
8.	3	2	1	6617.75	76.4143

9.	3	3	2	3936.21	71.9016

TABLE IX
RESPONSE TABLE FOR S/N RATIO IN FLOOD MACHINING

Level	Cutting Speed	Feed Rate	Depth of Cut
1	68.93	71.28	73.36
2	75.08	72.65	69.91
3	74.06	74.15	74.80
Delta	6.15	2.87	4.89
Rank	1	3	2

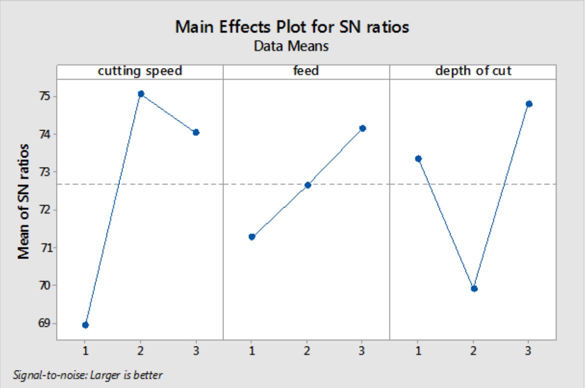

Fig. 3: Mean Signal to Noise Graph for MRR in Flood Condition

TABLE X
EXPERIMENTAL RESULTS FOR MRR AND S/N RATIO IN MQL MACHINING

Exp. No.	Cutting Speed	Feed	Depth of cut	MRR	SNRA1 (in dB)
1.	1	1	1	2019.59	66.1053
2.	1	2	2	3534.291	70.9660
3.	1	3	3	5697.6	75.1138
4.	2	1	2	4588.127	73.2327
5.	2	2	3	7180.8	77.1235
6.	2	3	1	7180.8	77.1235
7.	3	1	3	8568	78.6576
8.	3	2	1	6499.84	76.2581
9.	3	3	2	12161	81.6994

TABLE XI
RESPONSE TABLE FOR S/N RATIO IN MQL MACHINING

Level	Cutting Speed	Feed Rate	Depth of Cut
1	70.73	72.67	73.16
2	75.83	74.78	75.30
3	78.87	77.98	76.96
Delta	8.14	5.31	3.80
Rank	1	2	3

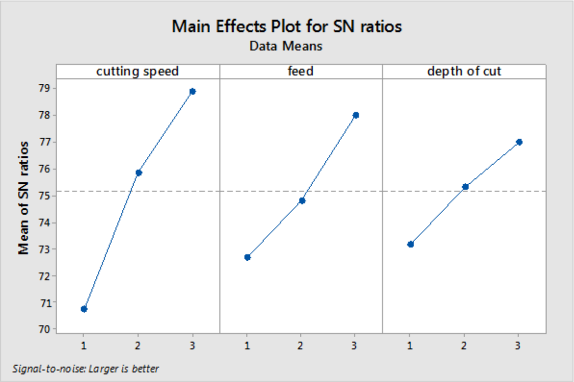

Fig. 4: Mean Signal to Noise Graph for MRR in MQL Condition

B. Surface Roughness

Surface Roughness is Easier to measure as compared to surface finish by using various instruments such as handy surf, tele surf, comparator, etc.

Lower is the surface roughness, Higher will be the Surface finish. So, from the three available modules of Taguchi Method, Smaller the Best Module is selected. The L9 OA for surface roughness in dry, flood as well as MQL machining is shown below:

TABLE XII
EXPERIMENTAL RESULTS FOR SURFACE ROUGHNESS AND S/N RATIO IN DRY MACHINING

Exp. No.	Cutting Speed	Feed	Depth of cut	Surface Roughness (in µm)	S/N ratio (in dB)
1.	1	1	1	1.97	-5.8893
2.	1	2	2	1.95	-5.8007
3.	1	3	3	1.90	-5.5751
4.	2	1	2	3.42	-10.6805
5.	2	2	3	3.53	-10.9555
6.	2	3	1	3.2	-10.1030
7.	3	1	3	4.28	-12.6289
8.	3	2	1	4.19	-12.4443
9.	3	3	2	5.47	-14.7597

TABLE XIII
RESPONSE TABLE FOR S/N RATIO IN DRY MACHINING

Level	Cutting Speed	Feed Rate	Depth of Cut
1	-5.755	-9.733	-9.479
2	-10.580	-9.733	-10.414
3	-13.278	-10.146	-9.720
Delta	7.523	0.413	0.935

Rank	1	3	2

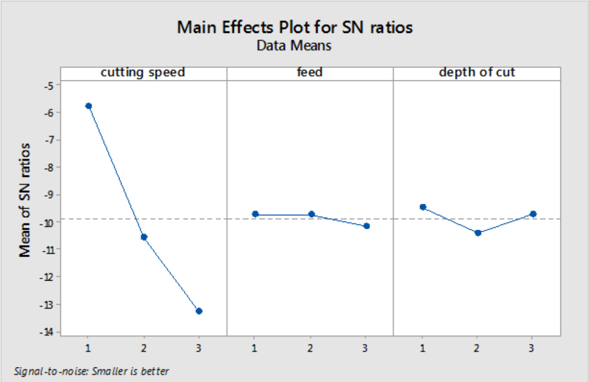

Fig. 5: Mean Signal to Noise Graph for Surface Roughness in Dry Condition

TABLE XIV
EXPERIMENTAL RESULTS FOR SURFACE ROUGHNESS AND S/N RATIO IN FLOOD MACHINING

Exp. No.	Cutting Speed	Feed	Depth of cut	Surface Roughness (in µm)	S/N ratio (in dB)
1.	1	1	1	1.77	-4.9595
2.	1	2	2	1.72	-4.7106
3.	1	3	3	1.89	-5.5292
4.	2	1	2	2.46	-7.8187
5.	2	2	3	3.73	-11.4342
6.	2	3	1	3.23	-10.1841
7.	3	1	3	4.09	-12.2345
8.	3	2	1	4.17	-12.4027
9.	3	3	2	5.68	-15.0870

TABLE XV
RESPONSE TABLE FOR S/N RATIO IN FLOOD MACHINING

Level	Cutting Speed	Feed Rate	Depth of Cut
1	-5.066	-8.338	-9.182
2	-9.812	-9.516	-9.205
3	-13.241	-10.267	-9.733
Delta	8.175	1.929	0.551
Rank	1	2	3

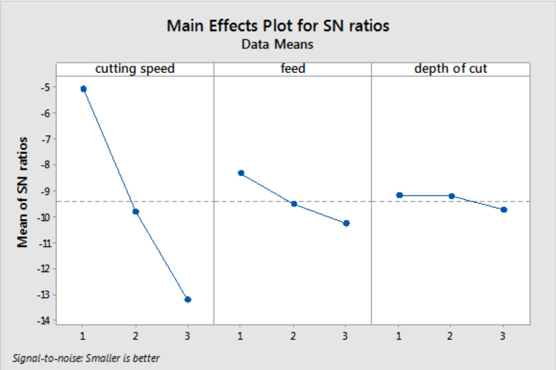

Fig. 6: Mean Signal to Noise Graph for Surface Roughness in Flood Condition

TABLE XVI
EXPERIMENTAL RESULTS FOR SURFACE ROUGHNESS AND S/N RATIO IN MQL MACHINING

Exp. No.	Cutting Speed	Feed	Depth of cut	Surface Roughness (in µm)	S/N ratio (in dB)
1.	1	1	1	1.59	-4.0279
2.	1	2	2	1.46	-3.2871
3.	1	3	3	1.76	-4.9103
4.	2	1	2	2.29	-7.1967
5.	2	2	3	3.05	-9.6860
6.	2	3	1	3	-9.5424
7.	3	1	3	3.8	-11.5957
8.	3	2	1	3.82	-11.6413
9.	3	3	2	4.67	-13.3863

TABLE XVII
RESPONSE TABLE FOR S/N RATIO IN MQL MACHINING

Level	Cutting Speed	Feed Rate	Depth of Cut
1	-4.075	-7.607	-8.404
2	-8.808	-8.205	-7.957
3	-12.208	-9.280	-8.731
Delta	8.133	1.673	0.774
Rank	1	2	3

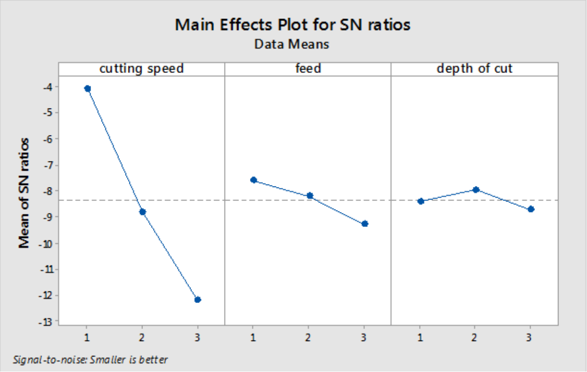

Fig. 7: Mean Signal to Noise Graph for Surface Roughness in MQL Condition

IX. RESULTS AND DISCUSSION

A. *Results for Material Removal Rate*

From the data collected by Taguchi method and optimization results, the optimum results for high MRR is calculated for three different conditions, dry, flood and MQL using Panama oil as a lubricant. The observations are recorded in the following table:

TABLE XVIII
COMPARISON TABLE FOR HIGH MRR IN DIFFERENT ENVIRONMENTAL CONDITION

S. No.	**Cutting Parameters**			**Environmental Condition**	**MRR**
	Cutting Speed	**Feed Rate**	**Depth of Cut**		
1.	190	0.4	0.15	Dry	10341.4
2.	190	0.4	0.15	Flood	3936.21
3.	190	0.4	0.15	MQL	12161

Thus, we can conclude that in MQL condition, using optimum cutting parameters, one could get desired high material removal rate.

From the response table generated for high MRR under three different environmental conditions, it can be concluded that:

- For DRY condition, cutting speed greatly affects MRR followed by feed rate and depth of cut.
- For FLOOD condition, cutting speed greatly affects MRR followed by depth of cut and feed rate.
- For MQL condition, cutting speed greatly affects MRR followed by feed rate and depth of cut.

B. *Results for Surface Roughness*

From the data shown in the above L9 OA, we came to the point that using MQL as cutting environment during machining operation, one could reduce the surface roughness of the machined surface of workpiece, i.e., a good quality, surface finish product can be obtained when compared to dry and flood environmental condition. Surface roughness increases under conventional cutting condition due to more intensive temperature and stresses at tool chip. MQL helps to overcome such problem and thus give better surface finish than conventional cutting processes depending on the workpiece material. The observations are recorded in the following table:

TABLE XIX
COMPARISON TABLE FOR SURFACE ROUGHNESS IN DIFFERENT ENVIRONMENTAL CONDITION

S. No.	**Cutting Parameters**			**Environmental Condition**	**Surface Roughness (in μm)**
	Cutting Speed	**Feed Rate**	**Depth of Cut**		
1.	130	0.3	0.15	Dry	1.95
2.	130	0.3	0.15	Flood	1.72
3.	130	0.3	0.15	MQL	1.46

From the response table generated for surface roughness under three different environmental conditions, it can be concluded that:

- For DRY condition, cutting speed greatly affects surface roughness followed by depth of cut and feed rate
- For FLOOD condition, cutting speed greatly affects surface roughness followed by feed rate and depth of cut.
- For MQL condition, cutting speed greatly affects surface roughness followed by feed rate and depth of cut.

C. *Types of Chips form*

Another phenomenon that can be observed from which effect of minimum quantity lubrication can be evaluated on tool and workpiece is interface is types of chips formed during machining.

Fig. 8: Actual Chips Formed in Dry Machining

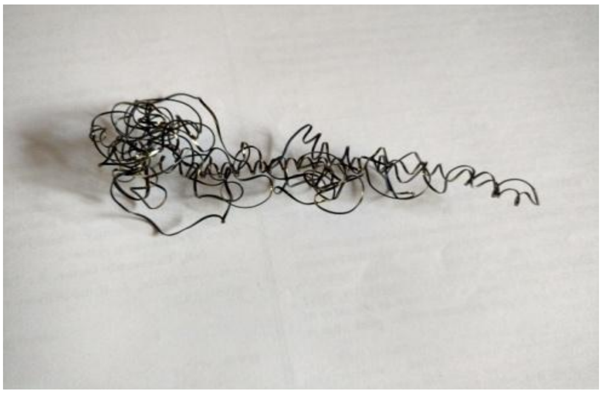

Fig. 9: Actual Chips Formed in Flood Machining

Fig. 10: Actual Chips Formed in MQL Machining

Fig. 8, 9, 10 shows that when En 31 steel is machined under dry condition, spiral chips are formed which are dark bluish in colour which depicts their burning thus stating that reduction in temperature is not prevalent. When Machining in wet conditions, spiral chips were produced and the colour of the chips is light bluish depicting high temperature between chip-tool interfaces was prevalent and reduction in temperature is very less. When machined under MQL, the form of this ductile chips change appreciably into more or less half turn and their surface appear little bit golden and brownish in colour. This indicated that the amount of reduction of temperature and presence of MQL enabled favourable chip-tool interaction.

X. CONCLUSION

The following conclusions can be drawn from the experiment

- Machining under MQL condition results in high material removal rate of workpiece when machined using optimum cutting parameters.
- The cutting performance of MQL machining is better than that of dry machining and conventional machining with flood cutting fluid supply.
- MQL is a technique that could reduce many cutting problems coming from high consumptions of lubricant, like high machining costs and environmental as well as workers health problems.

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