International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 07 Issue: 09 | Sep 2020 www.irjet.net p-ISSN: 2395-0072

Sustainable Machining of Alloy Steel 4140 with Minimum Quantity Lubrication (MQL)

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Abstract - *MQL (Minimum Quantity Lubrication) is reduced to the least amount necessary to the effective. Current manufacturing trends require large usage of cutting fluids which has led to adverse climatic changes and increased costs to the industries. Modern manufacturing industries are seeking different alternatives to attain the need of higher machining speeds, lower wastage and a better product quality as well as reducing the cost of the manufacturing process. The results are analyzed in terms of cutting force and surface roughness of the work piece machined with a coated carbide. Where the input parameters are cutting speed, feed rate and depth of cut. In this research work, Micro Mist Fluid ST-2020, plant-based cutting fluid has used as a cutting fluid. This cutting fluid has used under MQL mode for machining of alloy steel 4140. The results obtained from MQL machining using the plant-based cutting fluid have been analyzed and compared with dry machining and conventional wet machining. During wet machining, a stable milky white emulsion with water of soluble cutting fluid had applied. The tiny droplet size of fluid generated during MQL provided lesser cutting forces and better surface finish. Hence MQL may be a better option for eliminating fluid waste while maintaining the benefits of using a lubricant. Therefore, the application of MQL will reduce the use of cutting fluids, but the application of plant-based lubricants will eliminate the use of petroleum-based lubricants. Petroleum lubricants cause environmental pollution and may cause health risks to workers who come in direct contact with the cutting fluid.*

Key Words: Plant-Based Cutting Fluid, MQL Turning, AISI 4140.

1. INTRODUCTION

Minimum quantity lubrication (MQL) is a process that mixes a limited quantity of cutting fluid with pressurized air, which forms the fluid-air mixture. This fluid pressurized air mixture has then sprayed at the tool-chip interface by using a nozzle arrangement. This method ensures that it uses an only minute amount of cutting fluid compared to conventional lubrication (flood lubrication/wet lubrication) method used for machining. The cutting fluids used in the minimum quantity lubrication system had usually made from environment-friendly materials. Environment-friendly lubricants have costs higher than the lubricants made from crude oils. Still, MQL uses cutting fluid, which is approximately three or four orders of magnitude less than the quantity commonly used in wet lubrication method. Therefore the resultant cost of using environment-friendly lubricants is much less than the conventional way. The cutting fluid used for the current study is plant-based and biodegradable oil. The use of MQL has another benefit in terms of worker health. The use of conventional crude oil-based cutting fluids has hazardous health effects such as skin problems and difficulties in breathing.

Sustainable manufacturing approach means now days environmental development needs all industrial organizations, with practices known as sustainable, to strive at four actions that will assist the atmosphere across the entire supply chain.

- Reduction in electricity consumption
- Increase in energy consumption
- Reduced pollution
- Reduction in generated waste

The incorporation of sustainable manufacturing practices at all stages of output – commodity, method and device-would be sustainable. We learn the 3R because it is generally applicable to eliminating, reusing and recycling. This has to be expanded to incorporate other R's, such as eliminating, reusing, recycled, restoring, redesigning, repairing, refurbishing, landfill, etc. In order to be more effective, the cuts will start at the root. Consequently, sustainability in the architecture of the company will be integrated into the first component of initiative to compensate for the climate during the company's existence. The production of environmentally sound products will help successfully introduce and preserve them. The development of products that are easily destroyed helps in the repair, reuse and re-fabrication process. The design of products with ease of maintenance helps to increase the efficiency of product use.

MQL infrastructure has been planned to resolve a range of flood-related drawbacks and concerns. MQL requires less fluid and includes less energy, the biggest and most visible benefit. However, the correct application will greatly minimize wear of the instrument by the usage of the designed fluid supplied in the right position and in the right volume. There have been studies of improvements in tool life of over 50% (even occasionally nearly 100%). The performance and completeness of machined surfaces – better, more uniform finishing with fewer residual tension – can also be enhanced. The cutting method is leaner, improves the surface finish by proper lubrication and by splitting the chips instead of wrapping around the component. For other cutting operations, MQL may also aid to remove built-in lip. The improvement in machine wear often tends to keep surfaces more uniform. The chips are smoother and dryer with MQL. The prices for the production and storage of synthetic products are decreased and the use requires less oil. The total prices are usually smaller than the traditional systems for flood coolants.

Alloy Steel 4140 is a commonly used steel in industries. This steel has many useful properties, such as its being readily machinable and used for manufacturing parts, which include shaft, bolt, stud, gears, and axles. These things can be further surface-hardened to 50-55 HRC. In the present investigation, the Taguchi approach has used to determine which cutting parameters are more suitable for turning of Alloy steel 4140. This investigation tries to find a better combination of cutting speed, feed, and machining environment. To achieve optimum cutting parameters for reducing cutting forces and getting a better surface finish, manufacturing companies have restored the use of handbook-based knowledge and operators' expertise.

2. EXPERIMENTAL DETAILS

All experiments is performed at advance manufacturing lab on CNC lathe Setup, Walchand College of engineering Sangli. This experimentation work focused on the application of the design of experiment method for optimizing the process parameters in CNC turning of AISI 4140 with MQL mode using combined of two performance measures, surface roughness and cutting force.

2.1 Experimental Conditions

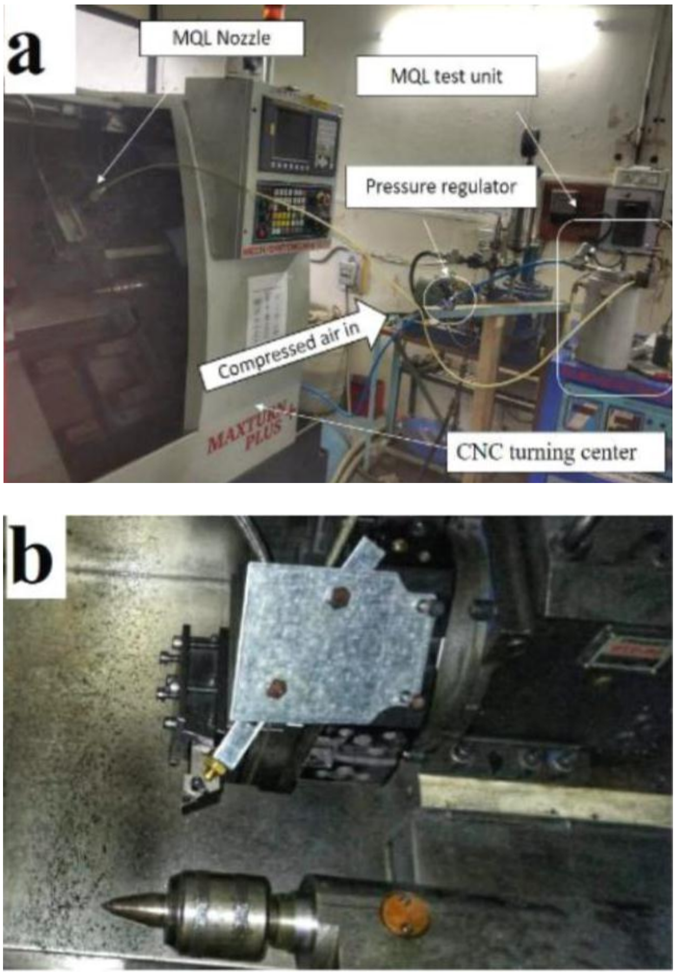
TNMG 16 04 08 carbide inserts mounted in MTJNL 2525 – M16 tool holder made by TRU-HOLD have used for the machining of Alloy steel 4140 (AISI 4140). The insert having a double-sided chip breaker used having a triangular shape, 0° normal clearance, 0.8 mm corner radius, and 4.76 mm thickness. Commercially available AISI 4140 bar has used for the investigation with a test length of 40 mm and 30 mm diameter. MAXTURN Plus + (MTAB) CNC turning center has used to carry out turning operations, as shown in Fig. 1. This figure also shows photographs of cutting insert and tool holder.

2.2 Environment Friendly Cutting Fluid

In the present study, Micro Mist Fluid ST-2020 has used as a cutting fluid. It is a premium plant-based metal cutting lubricant made by Nicotec™ India Corporation. As per the manufacturer's claim, this cutting fluid has properties like 100% environmentally safe, and it is excellent for cutting stainless steel material, useful for special-purpose cutting, etc. During the investigation, the supply air pressure has set at 5 bar, and the flow rate of cutting fluid was 100 ml/hr. The nozzle elevation angle was kept constant at 60° for each test. Table 1 describes the experimental parameters.

2.3 Output Responses

For the present experimentation, the two output parameters recorded viz. cutting forces and surface roughness. Cutting forces are directly related to the tool wear, power requirement of machine tool, self-excited vibrations, aesthetics, and ergonomics of the machined surface. Surface roughness is also an essential parameter in terms of the quality of the machined workpiece surface. To record surface roughness, Taylor Hobson make surface profilometer, has used. The dynamometer made by Kistler has was there to monitor the cutting forces. A new cutting insert has used for every test to maintain uniformity during each test.



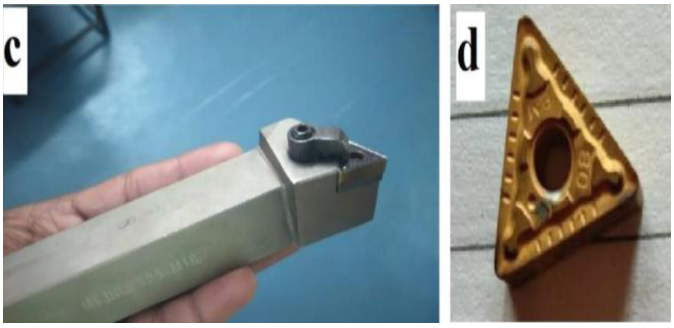


Fig. 1. (a) Experimental set up (b) Nozzle arrangement (c) Tool holder (d) Cutting tool insert

Following table shows the experimental conditions used for the study of effect of minimum quantity lubrication (MQL) in turning Alloy steel 4140.

Table 1. Experimental Conditions for the study of effects of MQL in turning AISI 4140.

Machine tool – CNC Turning Centre	MAXTURN Plus + (MTAB) CNC
Work specimen	Material AISI 4140
Size	Φ30 x 40 mm
Cutting insert	TNMG 16 04 08
Tool holder	MTJNL 2525 – M16
Corner radius	0.8 mm
Distance of cutting zone to the nozzle tip	20 mm
Nozzle elevation angle	60°
Cutting Speed	60, 80, 100 m/min
Feed rate (f)	0.10, 0.15, 0.2 mm/rev
Depth of cut (t)	0.5, 0.75, 1 mm
Environment	Dry, Wet & MQL
Cutting fluid	Micro Mist Fluid ST-2020 (Plant-Based Cutting Fluid)
Supply Air Pressure	5 bar
Cutting Fluid Flow Rate	100 ml/hr.

3. RESULTS AND DISCUSSIONS:

Here the experimentation is carried out at three different conditions means in dry machining using L9 orthogonal array, then by conducting experimentation by flood cooling method with same L9 orthogonal array and finally experiments were carried out by using minimum quantity lubrication (MQL) with same L9 orthogonal array and then data is being analyzed by ANOVA and Grey relation analysis (GRA). Experiments are conducted by taking input parameters as Speed, Feed and Depth of cut and the response variables recorded in each experimentation are cutting force and surface roughness.

3.1 Cutting Forces

This section discusses the evolution of cutting forces at different speeds, feed and cutting environments. In dry cutting mode, the cutting forces were continuously decreasing with an increase in speed. The average of cutting forces obtained in dry cutting mode was 2064.39N. The maximum cutting force and minimum cutting force found in dry cutting were 2681.21N and 1207.85N, respectively. The implementation of MQL greatly reduced cutting forces compared to dry mode, and wet mode. The average of cutting forces recorded during MQL turning was 768.18N. The maximum cutting force and minimum cutting force obtained in MQL cutting were 1105.51N and 493.72N, respectively. The lowest cutting forces have observed during the MQL cutting mode. The range of cutting forces have observed during the wet cutting mode has less than dry mode and more than MQL mode. The average of cutting forces during flood cooling turning was 732.03N, with 1370.08N maximum, and 444.91N minimum cutting force.

Table 2. Response Table for Signal to Noise Ratios (For Cutting Force)

Level	Cutting Speed, Vc (m/min.)	Environmental Condition	Feed, f (mm/rev)
1	-59.61	-57.23	-58.96
2	-55.81	-57.39	-57.77
3	-56.90	-57.70	-55.59
Delta	3.80	0.47	3.36
Rank	1	3	2

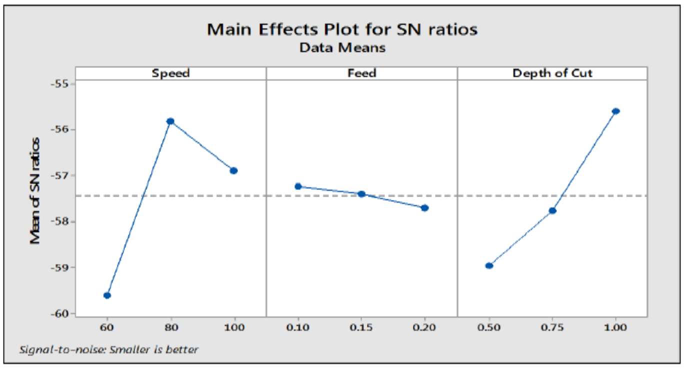


Fig. 2. Effects of Parameters of Cutting on Cutting Force

The effects of parameters of cutting on cutting force are measured, and trends have shown in Fig. 2 and Table 2 in tabular form. Hence as cutting speed, the S/N ratio for cutting force increases drastically from 60 m/min to 100 m/min, and as feed rate increases from 0.10 mm/rev to 0.14 mm/rev S/N ratio increases. Whereas when MQL cutting has used, the S/N ratio shows maximum value.

Table 3 shows that from the analysis of variance it is found that SPEED is the most significant parameter. Which contribute 57.11% from 100% which is max. It is proved by percentage contribution.

Table 3. ANOVA Results for Cutting forces

SOURCE	DF	Seq SS	Contribution	Adj SS	Adj MS	F- Value	P- Value
SPEED	2	190584	57.11%	190584	95292.1	11.74	0.078
FEED	2	307	0.09%	307	153.4	0.02	0.981
DEPTH OF CUT	2	126617	37.94%	126617	63308.5	7.80	0.114
ERROR	2	16232	4.86%	16232	8115.8		
TOTAL	8	333740	100.00%				
MODEL SUMMARY							
	S	R-sq	R-sq (adj)	PRESS	R-sq (pred)		
	90.0879	95.14%	80.55%	328691	1.51%		

3.2 Surface Roughness

The widely recognized arithmetic average height (Ra) value has determined by using the Taylor Hobson surface profilometer. The Ra value of each workpiece has measured five times and, the average of 5 readings has taken as Ra value of that corresponding workpiece to find out the surface roughness. The average Ra value obtained in dry cutting was 2.47 µm. The average Ra value obtained in MQL using Micro Mist Fluid ST 2020 was 1.80 µm, which is much less than that found in dry cutting, as shown in Fig.3. The average Ra value obtained in wet conditions has found 1.46 µm. The Ra value obtained in MQL turning is found most favorable than the Ra values in dry and wet turning. The least Ra value was recorded in MQL condition, which was 1.95 µm.

The result table of general linear model ANOVA analysis has shown in Table 5, which indicates that from analysis of variance it is found that depth of cut is the most significant parameter. Which contribute 45.37% from 100% which is max. It is proved by percentage contribution.

Table 4. Response Table for Signal to Noise Ratios (For Surface roughness)

Level	Cutting Speed, Vc (m/min.)	Environmental Condition	Feed, f (mm/rev)
1	-8.374	-7.486	-9.331
2	-8.319	-8.447	-10.033
3	-9.587	-10.346	-6.915
Delta	1.268	2.860	3.118
Rank	3	2	1

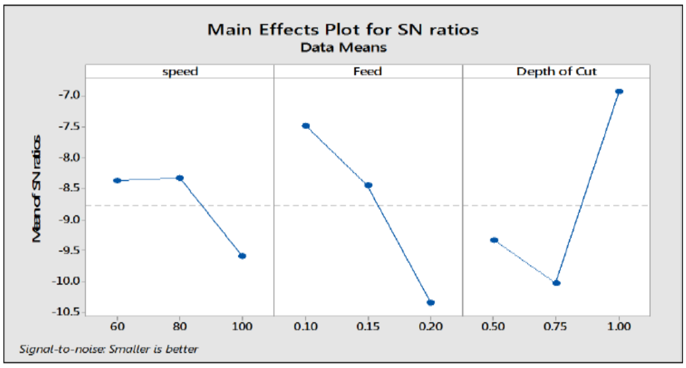


Fig. 3. Effects of Cutting Parameters on Surface Roughness

Table 5. ANOVA Results for Surface Roughness

SOURCE	DF	Seq SS	Contribution	Adj SS	Adj MS	F- Value	P- Value
SPEED	2	0.40142	11.33%	0.40142	0.20071	7.62	0.116
FEED	2	1.48096	41.81%	1.48096	0.74048	28.11	0.034
DEPTH OF CUT	2	1.60682	45.37%	1.60682	0.80341	30.50	0.032
ERROR	2	0.05269	1.49%	0.05269	0.02634		
TOTAL	8	3.54189	100.00%				
MODEL SUMMARY							
	S	R-sq	R-sq (adj)	PRESS	R-sq (pred)		
	0.162310	98.51%	94.05%	1.06695	69.88%		

3.3 Grey relation analysis for minimum value of cutting force and surface finish:

Grey system theory offers a proficient control on the uncertainty, multiple input and incomplete information. Method of GRA is an evaluation of the complete value of information variation among the sequences and furthermore employed to evaluate an almost accurate relationship among the sequences. It is an effectual approach to investigate the correlation among the sequences by means of less number of data and to examine several aspects. In GRA, initially the data attained from experiments are normalized. By using this normalized data, the grey relational co-efficient (GRC) are evaluated and the GRG is obtained by averaging the GRC values related to selected experimental results.

Table 6. Combine table for the analysis of the both parameter

S.N.	Speed	Feed	Depth of cut	Surface finish	Force
1	60	0.1	0.5	2.32	1105.514668
2	60	0.15	0.75	3.06	1048.127383
3	60	0.2	1	2.54	754.4526842
4	80	0.1	0.75	2.6	593.0439044
5	80	0.15	1	1.95	493.7234357
6	80	0.2	0.5	3.49	803.3890145
7	100	0.1	1	2.2	585.6863303
8	100	0.15	0.5	3.1	785.1405945
9	100	0.2	0.75	4.02	744.6079455
			MAX	4.02	1105.514668
			MIN	1.95	493.7234357

Table 7. Data Normalizing

Xi"(k)=(Max Xi (k)-Xi(k))/(Max Xi (k)-Min.Xi (k))	
Surface finish	Force
0.821	0.000
0.464	0.094
0.715	0.574
0.686	0.838
1.000	1.000
0.256	0.494
0.879	0.850
0.444	0.524
0.000	0.590

Table 8. Deviation Sequence

	Deviation sequence	
	Surface finish	Force
	0.179	1.000
	0.536	0.906
	0.285	0.426
	0.314	0.162
	0.000	0.000
	0.744	0.506
	0.121	0.150
	0.556	0.476
	1.000	0.410
Delta min	0.000	0.000
Delta max	1	1
Theta	0.5	0.5

Table 9. Gray relation coefficient and ranking

Gray relation coefficient		Gray relation grade	Finding the rank
Surface finish	Force		
0.737	0.333	0.535	5
0.483	0.356	0.419	9
0.637	0.540	0.588	4
0.614	0.755	0.685	3
1.000	1.000	1.000	1
0.402	0.497	0.449	7
0.805	0.769	0.787	2
0.474	0.512	0.493	6
0.333	0.549	0.441	8

From the ranking we understand that the fist rank is for the 5th set up which is Speed **80 m/min,** Feed **0.15 mm/rev,** Depth of cut **1 in mm.** For Minimization of both two-factor required above characteristics.

3.3.1 Combine Results:

From Experimentation and data analysis like Taguchi, ANOVA and GRA combined results are found and present here in the tabular form.

Table 10. Combine result table from data analysis

Optimization Techniques							
Sr. No.	Set up	Condition	Taguchi			ANNOVA	Gray relation
			Optimum value				
			Speed	Feed	Depth of cut	Response variable	1st rank of setup
1	Dry Machining	Min. Surface finish	100	0.1	1	Feed	5th set up
		Min. Cutting force	80	0.1	1	Speed	
2	Flood Cooling	Min. Surface finish	80	0.1	0.75	Speed	5th set up
		Min. Cutting force	80	0.1	0.75	Speed	
3	MQL	Min. Surface finish	80	0.1	1	Depth of cut	5th set up
		Min. Cutting force	80	0.1	1	Speed	

4. CONCLUSIONS:

Plant-based cutting fluid Micro Mist Fluid ST-2020 has used during the turning. Firstly machining parameters such as nozzle elevation angle, the distance of cutting zone to nozzle tip, etc. were selected by studying available literature and the lab conditions. Then the experiments were carried out by using appropriate settings. The following are the outcomes can be drawn from the present work:

- From the combine result we conclude that the 5th setup such as Speed 80m/min Feed 0.15 mm/rev Depth of cut 1mm is the optimum set up for obtaining minimum surface finish and minimum Cutting Force on the basis of Gray Relation Analysis.
- In Flood Cooling and MQL set up all parameter are nearly same so that the MQL set up is useful for the machining either than the Flood Cooling.
- MQL set up require less amount of coolant as compare to the Flood cooling and the result will be provided as it is.
- Biodegradable oil is used for cooling so that it is environment friendly and cheap cost so it's useful for machining purpose either than the oil-based coolant are environment hazardous.
- Ironically, several laboratory experiments have demonstrated that MQL machining can be a feasible option to Flood machining and can be environmentally safe. Much of the experiments were performed using MQL technology during metal turning operations with the usage of mineral oils, vegetable oils, and green cutting fluids.
- The results obtained from MQL turning has showed less cutting forces than results obtained from dry turning of AISI 4140.

5. ACKNOWLEDGEMENT:

The authors acknowledge the support provided by Advanced Machining Laboratory, Walchand College of Engineering Sangli (IN) and also like to thank the support from Sharp Edge Tools in MIDC Shiroli, Kolhapur. (IN).

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