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Experimental Study on Effect of Cutting Parameters on Chip-Tool Interface Temperature and Chip Formation in Turning EN-31 Hardened Steel Under Flooded and MQL Conditions

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Abstract

Hard turning is mainly used in industries to increase dimensional accuracy and surface finish so as to fulfill functional requirement of the product. In Hard turning cutting velocity (Vc) is high due to which high amount of heat is generated at the chip-tool interface which not only increase the tool wear and deteriorates the job quality but also has an effect on chips formation as chip formation indirectly indicate the rate of heat transfer under the influenced of machining environment. Therefore large amount of cutting fluid (flooded lubrication) is used to increase the performance of hard turning operation due to which it becomes easier to keep tight tolerances but on the other hand use of cutting fluid has become more problematic in terms of cost, disposal, wastage and environmental pollution. Minimum quantity lubrication (MQL) is a good alternative to this flooded lubrication. This study compares performance of MQL with flooded lubrication in turning EN-31 by using Response Surface Methodology (RSM). ANOVA was used to find out the significant parameters. The results indicated that when range of cutting parameters (cutting velocity, feed & D.O.C) was low to medium turning with MQL provides some favorable chips but with increase in Vc MQL totally fails to provide better results both in terms of favorable chips formation and reduction in chip-tool interface temperature (θ_i) as compared to flooded lubrication, thereby restricting the application of MQL to a certain range of parameter only.

Keywords: *Hard turning, MQL, chip-tool interface temperature (θ_i), chip formation, RSM*

1. Introduction

Turning is the most widely used machining process in industries. Industries mainly focus on the achievement of high quality turned parts in terms of surface finish, production rate, less wear on the cutting tools , economy in machining based on cutting fluids and favorable chip formation (chip shape, color and thickness) as it indirectly indicate the nature of chip-tool interaction which is helpful for determining the sources of increase in temperature, Hard turning is mainly used to increase surface finish and production rate but in hard turning large amount of heat is generated at the chip-tool interface mainly due to increase in cutting velocity therefore it becomes necessary to use cutting fluids to remove the heat generated thereby maintaining the economy of cutting tools but effecting the economy of coolant as very large amount of coolant is required i.e. coolant flow rate (flooded) for hard turning is generally 5 to 10 L/min depending upon cutting speed. Minimum quantity lubrication (MQL) is an established alternative to the traditional flood cooling as it come over the negative side of flood cooling. MQL also known as near dry machining (NDM), refers to the use of cutting fluids of very small amount typically of a flow rate of 50 to 500 ml/hour which is very less than the amount commonly used in flood cooling condition .The MQL technique consists of a mixture of drops of cutting fluids (neat oils or emulsions) in a flow of compressed air, generating a "spray" called as aerosols (mists) which is impinged with high velocity on the cutting zone through the nozzle. The Manner of lubricant supply is as important as total amount of lubricant supplied. That means the amount which actually reaches in the chip-tool interface as maximum heat is generated at chip –tool interface.

2. Literature Review

Prianka B. Zaman and N. R. Dhar [1] studied the effects of MQL on different machinability characteristics (cutting temperature, chip thickness ratio, tool wear and machined surface quality) of hard turned parts by using different cutting fluids (soluble oil, vegetable oil and VG 68 cutting oil), as compared to complete dry machining. The thickness of the chips was repeatedly measured by a slide caliper. The results indicated that the use of MQL with VG 68 cutting oil performed better in comparison to other cutting fluids and dry environment in respect of chips thickness ratio, cutting temperature, tool wear, surface roughness and dimensional deviation.

Khan and Dhar [2] investigated the role of MQL (Air: 7 bar; Flow rate: 60ml/h through external nozzle) using vegetable oil (food-grade, Viscosity: 84 centipoise at 20 °C) as compared to dry machining in turning AISI-1060 steel having hardness 245BHN at industrial speed-feed combinations. Results include significant reduction in tool wear rate, surface roughness by MQL mainly through reduction in the cutting zone temperature.

Panda.A et al. [3] has done study on hard turning of EN 31 steel (55HRC) under varying process parameters such as cutting speed, feed and depth of cut with respect to surface roughness using TiN/TiCN/Al_2O_3 multilayer coated carbide inserts through Taguchi L16 orthogonal array design by investigating Ra under dry environment. Machining time was fixed as 3 minute for each run. The surface quality appered better with increase in cutting velocity and with low feed rate, where as an increase in feed deteriorated surafce finish noted as detrimental factor from ANOVA study.

Prasanna P Kulkarni et al. [4] has performed experiments to determine the effect of cutting fluids and cutting parameters on chip formation mode and cycle time in turning of EN-24 and EN-31 material under dry & flooded condition. Based on the results of experimental investigation in wet condition Chip thickness is decreased at 210rpm to 450 rpm range as compared to dry with bright color (Golden color and light blue color) with smooth surface due to reduction in temperature for both materials.

3. Experimental Condition and Procedure

Experiments were carried out by plain turning of 38mm diameter and 75mm long rod of EN-31steel using a powerful and rigid semi-automatic geared lathe (Pioneer 250-PL, Rajkot, India) and new cutting edge for each run at different cutting velocities (*V*c) and feed rates (*S*o) and D.o.C (t) combination each at three different levels using Response Surface Methodology to study the effect of cutting parameters on chip-tool interface temperature and favorable chip formation under flooded and MQL conditions. The experimental condition is given in table.1 and output response with DOE is given in table.2. External MQL set up was designed in such a way that a mist is produced having a flow rate of 480 ml/hr. at a pressure of 4 bar impinged at cutting zone so that the aerosol or mist (air + coolant) reaches as close to the chip-tool and the work-tool interfaces as possible. The photographic view of the MQL set-up is shown in Fig.1.a,b & c.

Table: 1 Experimental Condition

Particulars	Description
Material	EN31(C:1.02 Si:0.26 Mg:0.42 Cr:1.25 Ni:0.14 Mo:0.025 S:0.022 P: 0.01),Hardness 55 to 57 HRC
Cutting Tool & tool geometry	(Coated carbide insert SNMG 120404) Tool Holder PSBNR 2525M 12, Tool geometry -6°,-6°,6°,15°,75°,0.4 mm
Input parameters	(Vc-59.69, 92.519, 143.256 m/min, So - 0.1,0.15,0.23 mm/rev and t -0.5, 0.8, 1.0 mm)
MQL Parameters	Supply pressure (4 bar), flow rate 480 ml/hr , aerosol jet velocity 75.26 mm/s ,nozzle dia 1.5mm , nozzle distance 15 mm above chip tool interface , nozzle position vertically downward ,
Environment	(Flooded - water to oil ratio 1: 10 and for MQL 1: 5) cutting fluid- water soluble

The figure clearly show the basic parts of the MQL set up. The set up of MQL is based on External supply i.e. coolant and compressed air is flown separately, firstly flow control valve is open due to which the stored coolant in the sump will flow vertically downward (passing from inner pipe) up to coolant pipe, at the end of coolant pipe the inner pipe is extended and nozzle is attached so as to increase the velocity and then compressed air is blown (passing from outer pipe) up to coolant pipe at the end compressed air will transmits its energy to the coolant/liquid jet and the jet will break into mist or aerosol (air + coolant).This aerosol is then supplied at the cutting zone.

Table 2: Design of Experiments with Observed Response i.e. machining time (Tm) & Avg Chip-tool interface temperature (θ_i) under flooded and MQL Conditions.

Exp. Run	Vc (m/min)	So (mm/rev)	t (mm)	θ_{if} (°C)	θ_{im} (°C)
1	59.69	0.1	0.5	39.9	53.2
2	143.256	0.1	0.5	85.2	122.6
3	59.69	0.23	0.5	51.3	64.5
4	143.256	0.23	0.5	95.5	135.2
5	59.69	0.1	1.0	50.2	88.7
6	143.256	0.1	1.0	90.7	158.8
7	59.69	0.23	1.0	60.4	98.2
8	143.256	0.23	1.0	106.3	170.3
9	59.69	0.15	0.8	49.8	79.4
10	143.256	0.15	0.8	95.8	149.5
11	92.519	0.1	0.8	65.5	98.6
12	92.519	0.23	0.8	75.6	110.7

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13	92.519	0.15	0.5	63.7	81.4
14	92.519	0.15	1.0	71.5	116.3
15	92.519	0.15	0.8	68.4	102.5
16	92.519	0.15	0.8	68.6	102.7
17	92.519	0.15	0.8	68.8	102.9
18	92.519	0.15	0.8	64.5	101.8
19	92.519	0.15	0.8	64.8	102.1
20	92.519	0.15	0.8	64.7	103.2

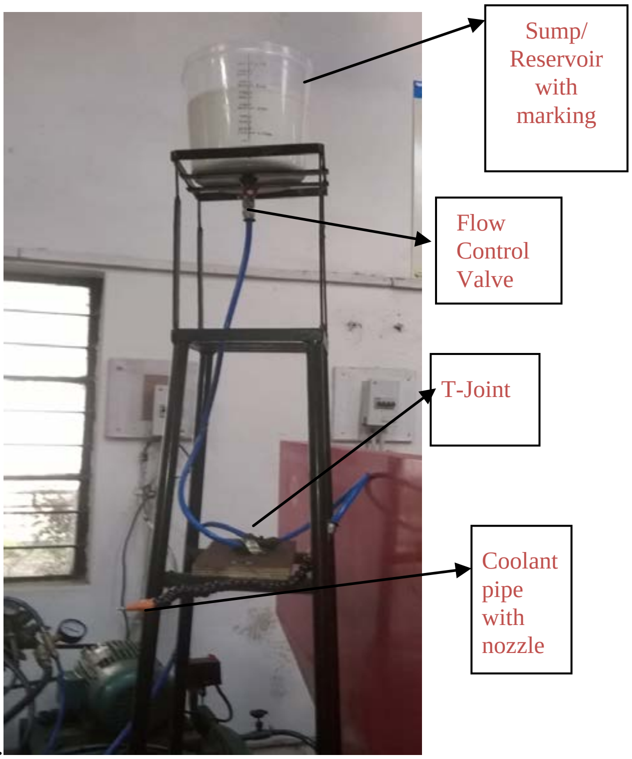

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Fig.1.a: Photographic view of External MQL Set- up

Fig.1.b: Photographic view of Co-Axial pipe

Fig. 1.c: MQL Nozzle supplying mist

4. Study of chip formation (chip shape, size and color) under Flooded and MQL system.

The chip color, thickness, shape, size etc. directly and indirectly indicate the nature of chip-tool interaction influenced by the machining environment. The chip samples were collected during each experimental run.

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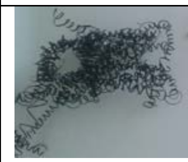
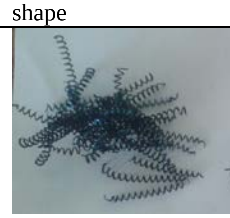
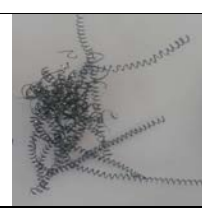
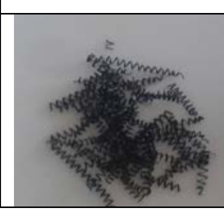
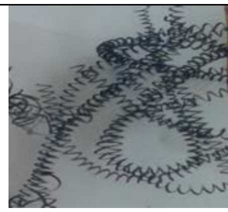
Table: 3 Images of chips formed under different cutting environments.

Run No	Flooded	MQL
1	 Silver grey segmented or half turn	 Golden continuous spiral
4	 Light Silver blue Long tubular	 Silver Bluish continuous helical
5	 Golden spiral continuous	 Brown Silver Discontinuous
6	 Brown Tangled ribbon shape	 Blue Tangled ribbon shape
7	 Dark Blue short tubular	 Dark Blue Black segmented or half turn
12		

	Silver Blue continuous	Dark Blue discontinuous
14	 Brown Short helical	 Blue Long spiral

It was found from visual inspection that mostly discontinuous chips, ribbon type chips, tubular chips and spiral chips were obtained during machining of EN31 with SNMG120404 insert under flooded and MQL conditions. EN31steel when machined under wet condition produced ribbon type continuous chips with more curl at medium to higher Vc (92.519 m/min to 143.256 m/min) and at low to medium feed rate (0.1 to 0.15 mm/rev) similarly under MQL at medium to higher Vc(92.519 m/min to 143.256 m/min) and at low feed rate (0.1 to 0.15 mm/rev) ribbon type continuous chips were obtained at some runs (Run No.6). The observations further showed that more discontinuous chips were obtained at Low Vc(59.69 m/min) when machining under flooded condition as compared to MQL and more discontinuous chips were obtained at medium Vc (92.519 m/min) when machined under MQL with more chip thickness as compared to flood cooling. Similarly more spiral shape chips were obtained under MQL as compared to flood cooling at low Vc.Also more continuous chips were produced while machining under MQL as compared to flooded condition at high Vc. When machined with MQL the shape of chips did change much as compared to flooded but their surface appeared darker then that appeared under flooded lubrication this indicates that the amount of reduction of temperature in case of flooded enabled favorable chip–tool interaction, where as chips formed under application of MQL shows that in most of the cases they are not favorable but at some runs favorable chips were obtained i.e. at low to medium cutting speed and feed range bright color chips were obtained.

5. Result and Discussion

The Analysis of variance (ANOVA) is a necessary test which is performed in most of the optimization process due to its accuracy in prediction of P-values. If the p-value is lower than 0.05 then the factor is significant.

5.1 Adequacy and ANOVA of the Model for θ_{if} :

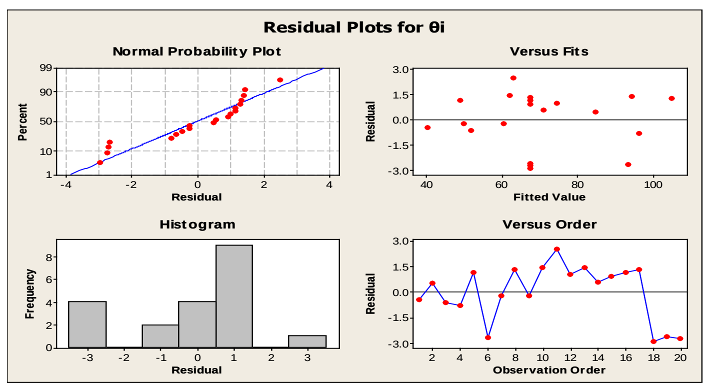
The analysis was done using uncoded units Avg Chip-tool interface Temperature (θ_{if}) = - 8.9431 + 0.5307Vc +89.2051 So + 17.3859 t

Table 4: Coefficient Table for Temperature (θ_{if})

Term	Coef	SE Coef	T	P
Constant	-8.9431	2.59751	-3.443	0.003
Vc	0.5307	0.01337	39.684	0.000
So	89.2051	8.58178	10.395	0.000
t	17.3859	2.23844	7.767	0.000
S = 1.78695 PRESS= 73.9170 R-Sq = 99.09% R-Sq(pred) = 98.69% R-Sq(adj) = 98.92%				

Table 5: ANOVA Table

Source	DF	Seq SS	Adj SS	MS	F	P	% of Contribution	
Vc	1	5043.91	5028.71	5028.71	1574.82	0.000	90.33	Most Significant
So	1	338.24	345.02	345.02	108.05	0.000	6.19	Significant
t	1	192.63	192.63	192.63	60.33	0.000	3.46	Least Significant
Total	19							



Graph 1: Residual Plot for Avg Chip-tool interface Temperature (θ_{if}) under flooded condition.

5.2 Adequacy and ANOVA of the Model for θi_m

The analysis was done using uncoded units

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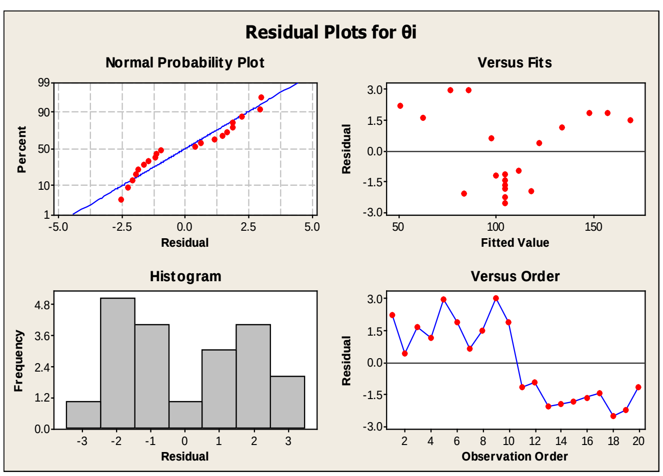
Avg Chip-tool interface temperature (θ_{im}) = -43.7777 + 0.8523Vc + 91.3077 So + 69.4982 t

Table 6: Coefficient Table for for Temperature (θ_{im})

Term	Coef	SE Coef	T	P
Constant	43.7777	3.01768	-14.507	0.000
Vc	0.8523	0.01554	54.852	0.000
So	91.3077	9.96994	9.158	0.000
t	69.4982	2.60053	26.725	0.000
S = 2.07600 PRESS= 109.039 R-Sq = 99.58% R-Sq(pred) = 99.33 % R-Sq(adj) = 99.50%				

Table 7: ANOVA Table

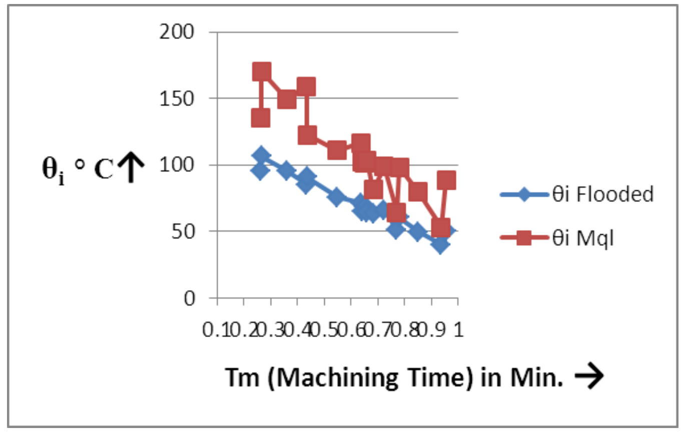
Source	DF	Seq SS	Adj SS	MS	F	P	% of Contribution	
Vc	1	12875.6	12967.1	12967.1	3008.75	0.000	79.03	Most Significant
So	1	333.9	361.5	361.5	83.87	0.000	2.20	Least Significant
t	1	3078.1	3078.1	3078.1	714.21	0.000	18.76	Significant
Total	19							



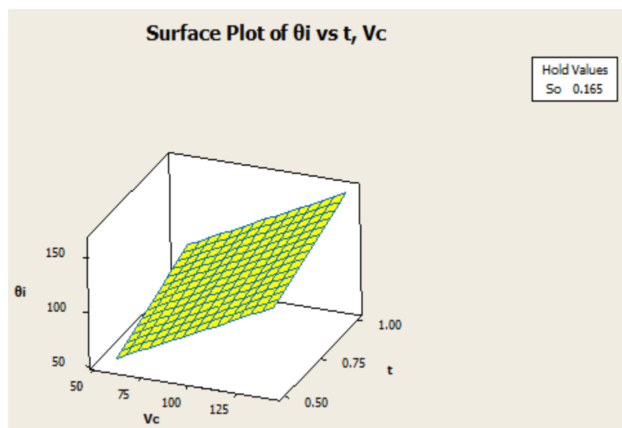
Graph 2: Residual Plot for Avg Chip-tool interface Temperature (θ_{im}) under MQL

6. Comparative Study of Flooded and MQL in terms of chip-tool interface temperature

As shown in graph it is clear that with decrease in machining time (Tm decreases mainly with increase in cutting velocity and feed rate) there is rise in the chip-tool interface temperature as shown in graph. Under MQL the increase in temperature obtained is high as compared to flooded with increase in the level of cutting parameters (Vc, So & t).



Graph 3: chip-tool interface temperature (θ_i) flooded vs. MQL



Graph 4: Response Surface Plot of Chip-tool interface Temp vs. Vc, t

Fig.2: Measurement of temperature using K- type infrared thermometer

7. Optimized results

The process optimization was done using RSM's D-Optimal Test. The optimized value of input parameters for the response is shown in the table below.

Table 8: Optimized results

Input parameters	Optimized value for **Flooded**	Predicted response for flooded	Optimized value for **MQL**	Predicted response for MQL
Vc (m/min)	137.2373	θ_i = 80.18 $^\circ$C Tm=0.449 Min	89.2335	θ_i = 76.79°C Tm=0.737 Min.
So (mm/rev)	0.10		0.1070	
t (mm)	0.5		0.5	

8. Conclusion

From the analysis of chip-tool interface temperature and chip formation in flooded and MQL system the following conclusions can be drawn:

1) By using MQL system very large amount of coolant can be saved also at some runs (when cutting velocity & feed was low to medium) the performance of MQL was near to flooded in terms of chip formation but with increase in cutting velocity,the color of chips surface appeared darker then that appeared under flooded lubrication.This indicates that the amount of reduction of temperature in case of flooded enabled favorable chip–tool interaction, where as chips formed under application of MQL shows that in most of the cases they are not favorable .

2) MQL totally fails to provide better results in terms of reduction in chip-tool interface temperature (θ_i) as compared to flooded lubrication, there by restricting the application of MQL to a certain range of parameter only i.e. optimized value for MQL found was medium cutting velocity (89.2335 m/min) , Low feed (0.1070 mm/rev) and low D.o.C (0.5 mm) where as flooded lubrication permitting use of high cutting velocity which is required for hard turning i.e. optimized value for flooded found was high cutting velocity (137.2373 m/min) , Low feed (0.10 mm/rev) and low D.o.C (0.5 mm).

It is clear that flooded lubrication system performance was better as compared to MQL in most of the experimental runs.

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