

MATERIAL REMOVAL RATE AND SURFACE ROUGHNESS ON GRINDING OF DUCTILE CAST IRON USING MINIMUM QUANTITY LUBRICATION

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ABSTRACT

A promising alternative to conventional fluid coolant application is minimum quantity lubrication (MQL). Despite much research, there have been few investigations about the influence of MQL parameters on the process results, such as oil flow rate, workpiece speed and depth of cut. The objective of this project is to develop a mathematical model of the material removal rate and surface roughness on grinding of ductile cast iron using minimum quantity lubrication. The experiment was carried out according to the design of experiment principle, prepared based on central composite design. The experimental data was utilized to develop the mathematical model for first- and second-order models. The second order gives acceptable performance of the grinding. The result shows that the highest value of the grinding ratio is with single-pass MQL, and the lowest value is with multiple-pass conventional coolants. The model fit was adequate and acceptable for sustainable grinding using a 0.15% volume concentration of ethylene glycol. This paper quantifies the impact of water-based ethylene glycol on the surface quality achieved. It is concluded that the surface quality is most influenced by the depth of cut and table speed. It is recommended that future research is also conducted using another parameter such as the speed of the grinding wheel or the distance from the wheel-workpiece contact zone. Besides that, further research can be conducted using different nozzle angles and different types of grinding wheel to see how these affect the surface of the material.

Keywords: Minimum quantity lubrication; grinding; material removal rate; surface roughness; cast iron.

INTRODUCTION

Grinding is one of the material removal processes that is widely used in industry, and is used in order to get a better surface quality and very close tolerance, which is very strict for design components [1]. When the tools make contact with the workpiece surface, the heat rises in the latter [2]. Coolant is used to enhance the performance of grinding in terms of giving a better surface finish, reducing the temperature between the surface contacts and also cleaning the surface from the chips generated during the grinding process [3]. Large quantities of emulsion-based cooling fluids for machining are still widely used in the metal-working industry, generating high consumption and disposal costs and having an impact on the environment [4]. The increasing need for environmentally friendly production techniques and the rapid growth of cutting fluid disposal costs have led to

demand for an alternative to the machining processes currently used. The introduction of Minimum Quantity Lubrication (MQL) makes use of a lubricant that replaces the conventional coolant in order to overcome the temperature and surface finish problems [5-8]. The use of coolant or cutting fluids is the most common strategy to solve this problem. However, the introduction of cutting fluids often produces air-borne mist, smoke and other particulates that affect the shop floor air quality. These products bring environmental, health and safety concerns. In addition, the cost of using cutting fluids is several times higher than the tool costs themselves. Environmental concerns have become increasingly important to productive processes, allied with their economic and technological aspects.

Green engineering is used to indicate environmental concerns in engineering. Green manufacturing is a subset of green engineering. Environmentally friendly machining is a part of green manufacturing. It is included in the concept of sustainable manufacturing, which considers economic and social concerns in addition to environmental concerns [9-12]. Environmentally friendly machining attempts to minimize the consumption of cutting fluid, cutting tools and energy. Green engineering is a modern manufacturing strategy, which has become popular as a sustainable development strategy in industrial processes and production. Dry machining and minimum quantity lubricant (MQL) machining have become the focus of attention of researchers and technicians in the field of machining as an alternative to traditional fluids[13, 14]. Silva, Bianchi [15] investigated the effects of grinding parameters on ABTN 4340 steel using the MQL technique. They found that the surface roughness, grinding force, diameter wear and residual stress improved with the use of the MQL system in the grinding process due to better lubrication of the grinding zone, and provided better slipping of grains at the contact zone. The concept of MQL is fundamentally different from that of flood coolant and this can be a large stumbling block to machinists who are new to MQL. MQL is an alternative intended to save money, while eliminating the mess, disposal and negative aspects of coolant use[11]. Ethylene glycol is one of the base fluids for nanofluid beside water, engine oil and cutting fluid. Ethylene glycol is also a chemical commonly used in many commercial and industrial applications including antifreeze and coolant. The major use of ethylene glycol is as a medium for convective heat transfer in, for example, car radiators, liquid-cooled computers, chilled water air conditioning systems, and the like [16]. The response surface method [17] is a statistical method that uses quantitative data from appropriate experiments to determine and simultaneously solve multivariate equations. It is useful for analyzing and modeling problems to obtain a response of interest that is influenced by several variables [18]. The objective of this study is to evaluate the performance of MQL on surface grinding in terms of MRR and surface roughness and to develop a mathematical model based on the response surface method, and additionally to optimize the process parameters using RSM.

METHODS AND MATERIALS

The response surface method uses quantitative data from experimental results to determine and simultaneously solve multivariate equations. The main objective of RSM is to get the response of interest, which is the material removal rate for each different coolant condition. To find the value of the MRR, the mass difference of the workpiece and also the time taken is used. Table 1 shows the design of the central composite design method.

$$MRR = \frac{\text{Mass difference}}{\text{Time aken}} \tag{1}$$

Table 1. Central composite design method for MRR.

Workpiece	Workpiece speed (rpm)	Depth of cut (μm)
A	25.2	2
B	25.2	4
C	25.2	6
D	12.5	2
E	12.5	4
F	12.5	6
G	8.7	2
H	8.7	4
I	8.7	6

Response surface methodology explores the relationships between several explanatory variables and one or more response variables. The main idea of RSM is to use a set of designed experiments to obtain an optimal response. In this study, RSM is utilized for establishing the relations between the different grinding coolant parameters with a variety of machining criteria and exploring their effects on the response as the MRR. The response of surface roughness and material removal rate is described by Eq. (2):

$$Y = C_0 + \sum_{i=1}^n C_i x_i + \sum_{i=1}^n C_{ii} x_i^2 + \sum_{i=1}^{n-1} \sum_{j=2}^n C_{ij} x_{ij} \tag{2}$$

where Y is the corresponding response, SR or MRR, yielded by the various grinding process variables, and x_i (1, 2, …, n) are coded levels of n quantitative process variables, while the terms C_0 , C_i , C_{ii} and C_{ij} are the second-order regression coefficients. The second term under the summation sign of this polynomial equation is attributable to the linear effect, whereas the third term corresponds to the higher-order effects; the fourth term of the equation includes the interactive effects of the process parameters. In this research, the equation can be written as Eq. [19]:

$$Y = C_0 + C_1 x_1 + C_2 x_2 + C_3 x_1 x_3 + C x_2^1 + C x_2^2 \tag{3}$$

where X_1 and X_2 , are the workpiece speed and depth of cut respectively.

G-Ratio

The G-ratio is the value of the material removal rate and the value of the tool wear. The workpiece material and the grinding wheel are important to find the G-ratio value. This value is shown as the interaction between the MRR and the tool wear. The higher the value of the G-ratio, the better the method of grinding. To find the value of the G-ratio, Eq. (4) is used.

$$G - \text{ratio} = \frac{\text{Material removal rate}}{\text{Tool wear}} \tag{4}$$

RESULTS AND DISCUSSION

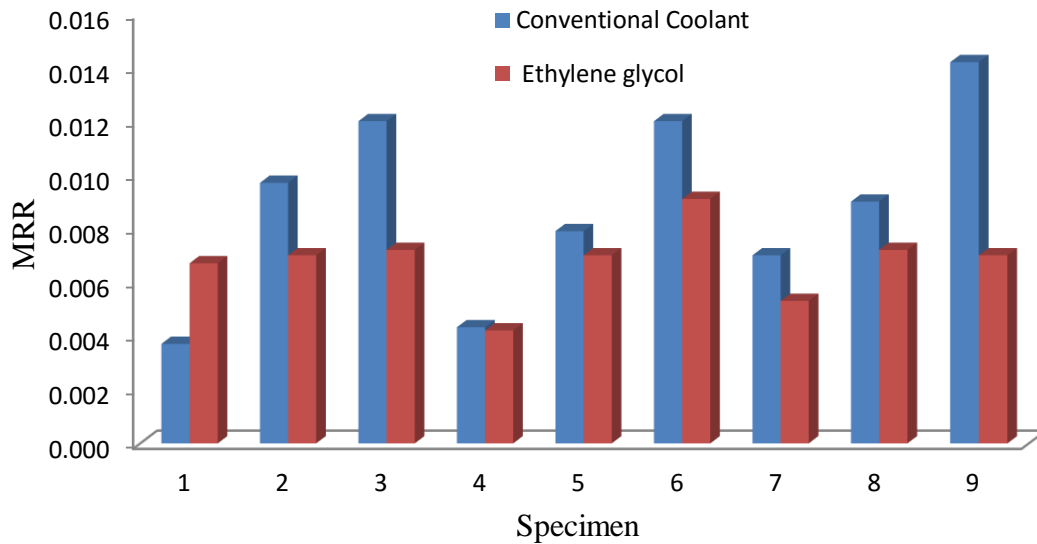
The material removal rate is the rate at which material is removed per unit time, and the unit is grams per second (g/s). The material removal rates for ethylene glycol with MQL and conventional coolant for the single-pass and multiple-pass grinding processes are represented in Table 2. The experiment was conducted nine times with various combinations of workpiece speed and depth of cut. A 5% volume concentration of soluble oil coolant and a 15% volume concentration of ethylene glycol were used. It can be observed that the minimum MRR in single-pass grinding using the conventional coolant was 0.00370 g/s. However, the minimum material removal rate was 0.00420 g/s for the ethylene glycol with the combination of the table speed and depth of cut. On the other hand, the maximum value is 0.01420 g/s and 0.00910 g/s for the conventional coolant and the ethylene glycol respectively. It is slightly different in multiple-pass grinding. The minimum MRR in multiple-pass grinding using a conventional coolant was 0.01560 g/s. However, the minimum MRR was 0.02090 g/s for ethylene glycol. The result for multiple-pass grinding shows that the depth of cut affects the MRR value. Besides that, multiple-pass grinding also gives higher values of MRR than single-pass. This is because in multiple-pass the grinding wheel passes the specimen ten times.

Table 2. Material removal rate for each coolant in different grinding conditions.

Specimen	Workpiece speed (rpm)	Depth of cut (µm)	Material removal rate (g/s)			
			Single-pass		Multiple-pass	
			Conventional coolants	Ethylene glycol with MQL	Conventional coolants	Ethylene glycol with MQL
1	8.7	2	0.00370	0.00530	0.04780	0.02670
2	8.7	4	0.00970	0.00700	0.01560	0.02670
3	8.7	6	0.01200	0.00720	0.04080	0.02400
4	12.5	2	0.00400	0.00420	0.01750	0.02340
5	12.5	4	0.00790	0.00700	0.02110	0.02630
6	12.5	6	0.01200	0.00910	0.08250	0.03000
7	25.2	2	0.00700	0.00530	0.06620	0.02090
8	25.2	4	0.00900	0.00720	0.08190	0.02510
9	25.2	6	0.01420	0.00700	0.15670	0.02901

Figure 1 shows the comparison between the conventional coolant and ethylene glycol with MQL for single- and multiple-pass grinding processes. Multiple-pass gives a higher MRR value compared to the single-pass. The MRR is slightly lower when using ethylene glycol (MQL) but the MRR value is higher when using conventional coolant. This is due to the effect of the nanoparticles that lubricate the two surfaces that slide over each other. Besides that, RSM is used to obtain the performance measure for the response of interest that is the material removal rate from the surface of the material. Tables 3 and

4 show analysis of variance for conventional coolant and ethylene glycol respectively. The result shows the consistently good performance of the grinding machine with a significant p-value of analysis of variance that is less than 0.05, while the lack of fit is more than 0.05 and the R-square value is more than 90%. This implies that the data is fit and adequate for further analysis and that all the parameters have significance for the grinding performance.



(a) single-pass grinding.

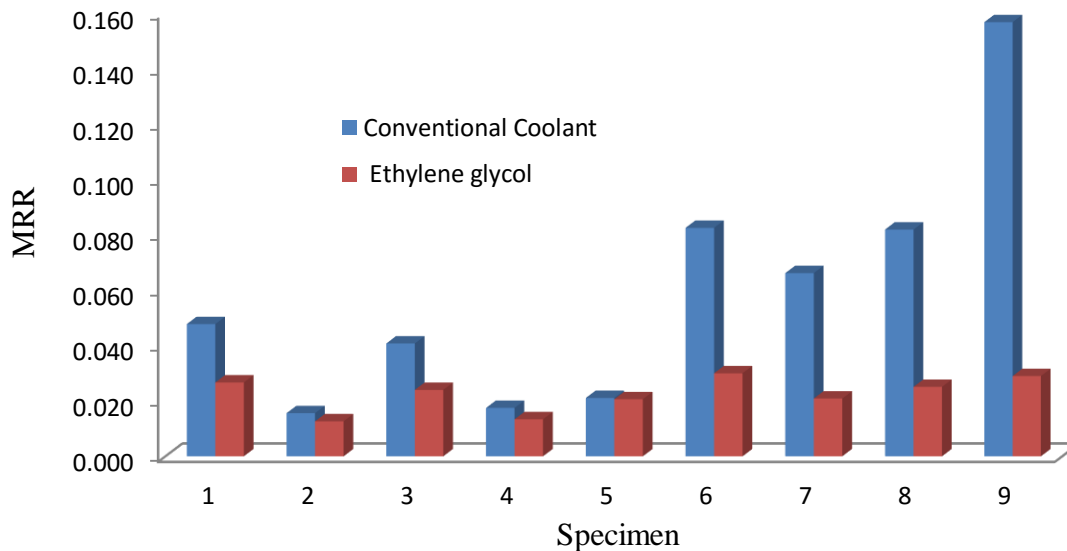


Figure 1. Materials removal rate for single- and multiple-pass grinding.

Table 3. RSM for single-pass and multiple-pass with conventional coolant.

Term	Coef	SE Coef	T	P	R ²
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Single-pass					
Constant	0.027384	0.000506	54.114	0.000	91.77%
Workpiece speed	0.000027	0.000206	0.132	0.001	
DOC	0.001784	0.000210	8.493	0.000	
Workpiece speed × Workpiece speed	-0.001704	0.000526	-3.240	0.004	
DOC ×DOC	-0.000227	0.000356	-0.638	0.530	
Workpiece speed × DOC	-0.002593	0.000240	-10.787	0.000	
Lack of fit				0.197	
Multiple-pass					
Constant	0.007428	0.000181	41.290	0.000	92.85%
Workpiece speed	0.000217	0.000074	2.943	0.008	
DOC	-0.0001859	0.000075	-11.418	0.000	
Workpiece speed × Workpiece speed	-0.0000784	0.000188	-4.161	0.000	
DOC × DOC	-0.000289	0.000128	-2.266	0.034	
Workpiece speed × DOC	-0.001626	0.000086	-18.886	0.000	
Lack of fit				0.115	

Table 4. RSM for single-pass and multiple-pass of ethylene glycol.

Term	Coef	SE Coef	T	P	R ²
Single-pass					
Constant	-0.01529	0.000534	-28.653	0.000	99.94
Workpiece speed	-0.003331	0.000217	-153.663	0.000	%
DOC	0.02055	0.000222	92.791	0.000	
Workpiece speed × Workpiece speed	0.06449	0.000555	116.267	0.000	
DOC × DOC	0.02859	0.000375	76.141	0.000	
Workpiece speed × DOC	-0.02398	0.000253	-94.601	0.000	
Lack of fit				0.153	
Multiple-pass					
Constant	0.007992	0.000196	40.842	0.000	98.65%
Workpiece speed	0.000378	0.000080	4.752	0.000	
DOC	0.003571	0.000081	43.951	0.000	
Workpiece speed × Workpiece speed	0.001496	0.000203	7.354	0.000	
DOC × DOC	-0.0000182	0.000138	-1.323	0.200	
Workpiece speed × DOC	-0.0001301	0.000093	-13.991	0.000	
Lack of fit				0.211	

The adequacy of the second-order model is verified using the P-value of lack of fit. At a level of confidence of 95%, the model is checked for this adequacy. Based on ANOVA analysis, the predictions of the material removal rate in both the single-pass and

multiple-pass grinding process using ethylene glycol are presented in Tables 3 and 4 respectively. The model is adequate due to the fact that the P-values lack of fit is insignificant. The lack of fit values are 0.153 for single-pass grinding and 0.211 for multiple-pass, which is greater than 0.05. This implies that both models are fit and adequate for further analysis. The second-order equation used to predict the MRR in the single-pass and multiple-pass grinding process for ethylene glycol can be expressed as Eq. (5) and Eq. (6) respectively:

$$MRR_{Secondord\sigma, sin glepass} = -0.0159 - 0.03331x_1 + 0.02055x_2 - 0.02398x_1x_2 + 0.006731x_1^2 + 0.0005342x_2^2 \tag{5}$$

$$MRR_{Secondord\sigma multipass} = 0.007992 + 0.000378x_1 + 0.003571x_2 - 0.001301x_1x_2 + 0.113452x_2^1 - 0.1234x_2^2 \tag{6}$$

Table 5 lists the data of the experimental and predicted values of the MRR model. The predicted and experimental values are closely related. This is because the percent error between the predicted and experimental values is less than 7.5%.

Table 5. Differentiation between experimental and predicted values of MRR.

Specimen	Depth of cut (µM)	Material removal rate (G/S)					
		Single-pass			Multiple-pass		
		Experimental	Prediction	Error (%)	Experimental	Prediction	Error (%)
1	2	0.0091	0.0090	1.10	0.0254	0.0260	2.36
2	4	0.0071	0.0070	1.41	0.0261	0.0260	0.38
3	6	0.0040	0.0040	0.00	0.0250	0.0250	0.00
4	2	0.0070	0.0070	0.00	0.0231	0.0230	0.43
5	4	0.0065	0.0070	7.69	0.0273	0.0270	1.10
6	6	0.0072	0.0070	2.78	0.0293	0.0300	2.39
7	2	0.0052	0.0050	3.85	0.0227	0.0210	7.49
8	4	0.0062	0.0061	1.61	0.0250	0.0260	4.00
9	6	0.0071	0.0070	1.41	0.0320	0.0300	6.25

Surface Roughness

Surface roughness was used to determine the quality of the workpiece characteristics, such as the minimum tolerance, lubricant effectiveness and the component life. Table 6 shows the surface roughness under different coolants and types of grinding. The reading was taken three times and the average is calculated. A good and better quality surface is with arithmetic mean roughness, Ra, below 0.8 µm (Rahman et al., 2014). Different types of grinding combined with different coolant flow rates and different types of coolant lead to good results where all the outcomes or surface roughness values are less than 0.8 µm.

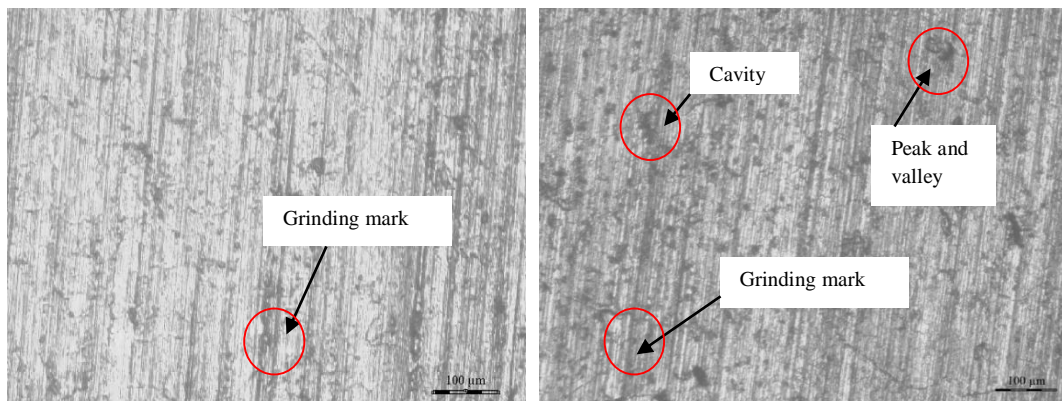
Table 6. Surface roughness for each coolant and different types of grinding.

Specimen	Workpiece speed (rpm)	Depth of cut (µm)	Surface roughness (µm)			
			Single-pass		Multiple-pass	
			Conventional coolants	Ethylene glycol (MQL)	Conventional coolants	Ethylene glycol (MQL)
1	8.7	2	0.21400	0.44100	0.29110	0.37900
2	8.7	4	0.16430	0.35900	0.33730	0.421100
3	8.7	6	0.25760	0.43200	0.54720	0.53300
4	12.5	2	0.24300	0.46300	0.38300	0.39800
5	12.5	4	0.17300	0.33300	0.41820	0.36100
6	12.5	6	0.23400	0.34700	0.53200	0.40600
7	25.2	2	0.35600	0.55000	0.36720	0.41100
8	25.2	4	0.25300	0.41700	0.38420	0.37700
9	25.2	6	0.31900	0.41900	0.48250	0.40800

The RSM for surface roughness shows the good performance of the grinding machine with a significant p-value of analysis of variance that is below 0.05, with lack of fit more than 0.005 and the R-square value more than 90%. This implies that all the data is fit and adequate. This shows that all the parameters have significance for the grinding performance and surface roughness. The second-order linear equations used to predict the surface roughness in the single- and multiple-pass grinding processes of ethylene glycol are Eq. (7) and Eq. [19] respectively:

$$SR_{Firstorder,singlepass} = 0.28592 - 0.02428x_1 - 0.04041x_2 + 0.03042x_1x_2 + 0.04762x_2^1 + 0.1053x_2^2 \tag{7}$$

$$SR_{Firstorder,multipass} = 0.36273 + 0.01456x_1 + 0.03681x_2 + 0.03940x_1x_2 + 0.135x_2^1 + 0.023x_2^2 \tag{8}$$



(a) Grinding using ethylene glycol. (b) Grinding using conventional coolant.

Figure 2. Scanning 2D microscope.

Table 7 lists the experimental and predicted results for surface roughness. The predicted and experimental values are closely related. The error between the predicted and experimental results is within 10%, which is reasonable and acceptable. Figure 2 shows the surfaces of the specimens for ethylene glycol and conventional coolant. No cavities, peaks or valleys are seen on grinding using ethylene glycol. This shows that

ethylene glycol removed the heat and reduced friction better than the conventional coolant.

Table 7. Differentiation between experimental and predicted results for surface roughness.

Specimen	Depth of cut (µm)	Surface roughness (Ra), µm					
		Single-pass			Multiple-pass		
		Experimental	Prediction	Error (%)	Experimental	Prediction	Error (%)
1	2	0.4410	0.4510	2.27	0.3790	0.3760	0.79
2	4	0.3590	0.3680	2.51	0.4210	0.4130	1.90
3	6	0.4320	0.4320	0.00	0.5330	0.5280	0.94
4	2	0.4360	0.4600	5.50	0.3980	0.3890	2.26
5	4	0.3330	0.3300	0.90	0.3610	0.3650	1.11
6	6	0.3470	0.3470	0.00	0.4060	0.4200	3.45
7	2	0.5500	0.5610	2.00	0.4110	0.3760	8.52
8	4	0.4170	0.4160	0.24	0.3770	0.4130	9.55
9	6	0.4190	0.4200	0.24	0.4080	0.4280	4.90

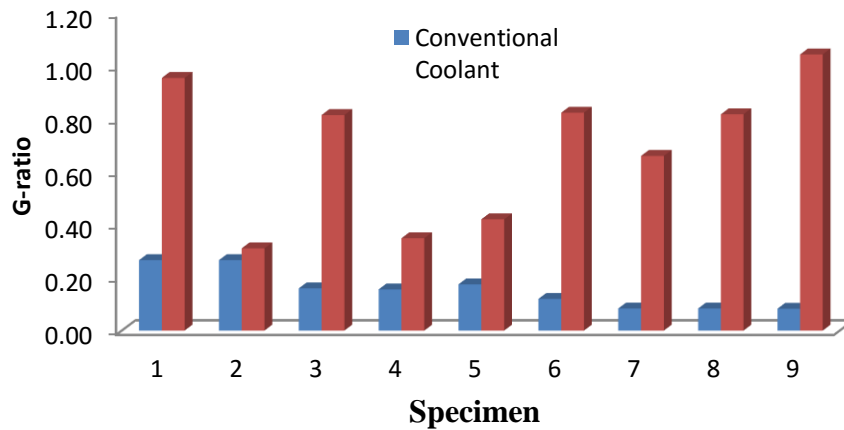
Tool Wear and G-Ratio

The G-ratio is the value of material removal rate per value of tool wear. This value shows the interaction between the MRR and tool wear. The higher the value of the G-ratio, the better the grinding method is. Tool wear occurs when there is metal-to-metal contact between the chip and workpiece, especially under very high stress at high temperature. This situation is further aggravated due to the existence of extreme stress and temperature gradients near the surface of the tool. For this experiment, the tool wear was measured. The measurement was taken three times. During grinding, cutting wheels remove material from the workpiece to achieve the required shape, dimension, and surface roughness. However, tool wear occurs during the grinding action and will ultimately result in the failure of the cutting wheel. When the tool wear reaches a certain level (0.3 mm), the tool has to be replaced to guarantee the desired cutting action. The tool wear was measured in mm using a Taylorsurf profilometer. Several readings were taken and the average was calculated. Table 8 illustrates the tool wear for ethylene glycol and conventional coolant. In industry, tool wear should be minimized to ensure a good quality finish, precision, and cost. It can be seen that the pattern of the wear increases as the depth of cut and table speed increase for multiple-pass grinding. The ethylene glycol reduces the wear by almost 50% compared to the conventional coolant. This is due to the ethylene glycol reducing the friction between the two contact surfaces.

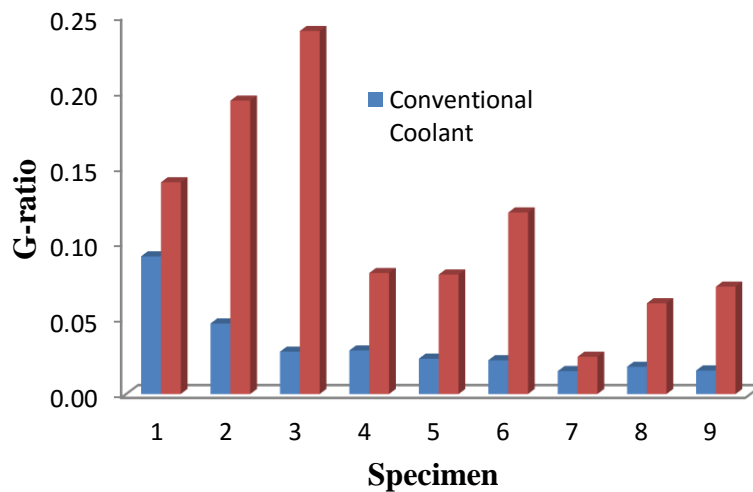
Table 8. Tool wear for each coolant and type of grinding.

Specimen	Tool wear (cm)	
	Single-pass	Multiple-pass

	Workpiece speed (rpm)	Depth of cut (μm)	Conventional coolants	Ethylene glycol (MQL)	Conventional coolants	Ethylene glycol (MQL)
1	8.7	2	0.10	0.05	0.10	0.05
2	8.7	4	0.10	0.05	0.15	0.05
3	8.7	6	0.15	0.05	0.15	0.05
4	12.5	2	0.15	0.05	0.25	0.05
5	12.5	4	0.15	0.10	0.30	0.10
6	12.5	6	0.25	0.10	0.30	0.10
7	25.2	2	0.25	0.10	0.35	0.15
8	25.2	4	0.30	0.10	0.40	0.15
9	25.2	6	0.35	0.15	0.45	0.20



(a) Single-pass grinding



(b) Multiple-pass grinding

Figure 3. G-ratio of single- and multiple-pass grinding with different coolants.

From Table 9 and Figure 3, it can be concluded that single-pass grinding with ethylene glycol has the highest value of G-ratio, followed by single-pass conventional coolant, multiple-pass ethylene glycol and lastly multiple-pass conventional coolant. As stated before, a higher value of G-ratio means that the method of grinding is better. It is

concluded that the type of coolant as well as the type of grinding influence the G-ratio. Single-pass has a slightly higher G-ratio value compared to multiple-pass because single-pass only passes the specimen once, compared with 10 times with the multiple-pass.

Table 9. G-ratio for each coolant and type of grinding.

Specimen	Workpiece speed (rpm)	Depth of cut (μm)	Tool wear (cm)			
			Single-pass		Multiple-pass	
			Conventional coolants	Ethylene glycol (MQL)	Conventional coolants	Ethylene glycol (MQL)
1	8.7	2	0.267	0.956	0.091	0.140
2	8.7	4	0.267	0.312	0.047	0.194
3	8.7	6	0.160	0.816	0.028	0.240
4	12.5	2	0.156	0.350	0.029	0.080
5	12.5	4	0.175	0.422	0.023	0.079
6	12.5	6	0.120	0.825	0.022	0.120
7	25.2	2	0.084	0.662	0.015	0.025
8	25.2	4	0.084	0.819	0.018	0.060
9	25.2	6	0.083	1.045	0.016	0.071

CONCLUSIONS

The mathematical model of the material removal rate and surface roughness in the grinding of ductile cast iron using minimum quantity lubrication has been developed using the response surface method. The difference in performance of cast iron using ethylene glycol in terms of the material removal rate is insignificant compared to conventional coolant. In terms of tool wear, conventional coolant shows higher values than ethylene glycol. Besides that, between single-pass and multiple-pass, the multiple-pass showed higher values of tool wear. This is because it has an effect on the G-ratio value. The higher the value of the G-ratio, the better the grinding method is. Therefore, the MRR should be maximized and at the same time the tool wear should be minimized for improved surface finish, cost and quality. So in terms of the G-ratio, ethylene glycol is more significant compared to conventional coolant. Besides that, the higher the oil flow rate, the better the surface of cast iron produced. In conclusion, MQL provides better performance and is also more environmentally friendly.

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