An analysis of frictional coefficient and surface roughness in surface grinding of SKD 11 tool steel using Minimum Quantity Lubrication (MQL) and dry techniques

M. Khoirul Effendi¹, Bobby O. P. Soepangkat¹, Rachmadi Noorcahyo², I Made Londen Batan¹, Arif Wahyudi¹, Dinny Harnany¹

¹ Mechanical Engineering Department, Institut Teknologi Sepuluh Nopember. Kampus ITS, Sukolilo, Surabaya 60111, Indonesia
Email: khoirul_effendi@me.its.ac.id

² Mechanical Engineering Department, Universitas Gajah Mada. Jl. Yacaranda Sekip unit IV, Blimbing Sari, Caturtunggal, Kec. Depok, Kabupaten Sleman, Daerah Istimewa Yogyakarta, 55281, Indonesia

Abstract. This study was intended to investigate the effect of the cooling method (CM), workpiece speed ($V_f$), and depth of cut (doc) on frictional coefficient (FC) and surface roughness (SR) in the surface grinding of SKD 11 tool steel. CM consists of minimum quantity lubrication (MQL) and dry techniques. Power function was applied to model both FC and SR. Based on the analysis of the model, CM and VF significantly affected both responses, while doc influenced only FC. SEM photographs of the ground surfaces were also presented to compare the surface quality between MQL grinding and dry grinding.

Keywords: Dry, MQL, frictional coefficient (FC), surface roughness (SR), surface grinding

1. Introduction

Grinding is considered as one of the abrasive machining processes and commonly used to produce precision components that require both high surface quality and fine tolerances. In this process, material removal occurs because of shearing and ploughing action caused by the interaction between workpiece and abrasive grains. The complex removal of material in the grinding process results in a higher specific energy requirement than other machining processes. Due to the larger chip sizes, the impact of ploughing and sliding can be considered insignificant in the grinding process [1]. The usage of a smaller depth of cut is applied and escalating the number of passes and high friction at contact interfaces. As a result, it creates large specific grinding energy, as well as a significant amount of heat. This high generation of heat produces thermal damage to workpiece and abrasive grains.

The flood cutting can eliminate the heat from the cutting zone area in the interface of the workpiece and grinding wheel, yet it could not be constantly found to be effective. Furthermore, it spends a substantial quantity of cutting fluid (about 8 litres/minute [2]), which arousing a critical question regarding the environmental and economic sustainability of the flood cutting. It has been reported by Singh et al. [3] that the ecology and workshop environment has been affected...
significantly by grinding fluids. In the manufacturing sector, there is a significant increase in the application of petroleum-based lubricants with annual increment as much as 1%, which is equal to about 13,700 million tons of oil [4]. This paradoxical condition pushed researchers in this area to discover novel and effective solutions.

There have been a number of studies that have been done to develop the minimum usage of cutting or grinding fluids. Some of the approaches used to minimize the quantity of grinding fluids are high pressurized coolants, cryogenic coolants, air/gas/vapor coolant, solid lubricants and the most prominent is minimum quantity coolant (MQL) [5]. The MQL system delivers extremely small quantities of cutting fluid (about 10,000 times smaller than conventional or flood cooling) for all machining processes. Since the amount of cutting fluid is so small, so MQL resembles dry machining processes. The aerosol or oil-air mixture is sprayed into the cutting zone. By applying this method, the manufacturing industry would be free of consuming a big quantity of fluids, repository, and disposal problem.

The rewarding effect of MQL in the milling process has been studied by Mia et al. [6-8]. They declared that under different circumstances, MQL demonstrates preferably result compared to the dry mode of the cutting process. Their analysis has shown that using the MQL method the lubricant can reach the grinding zone perfectly. Moreover, MQL can also help in promoting green manufacturing. A comparative study of the grinding process of AISI S52100 steel without using lubrication (dry), wet, and MQL has been performed by Mao et al. [9]. There were three characteristics compared, i.e., surface quality, grinding forces, and temperature. The evaluation showed that the MQL grinding process could achieve better surface quality and lowering down both grinding forces and temperature. Specifically, the grinding process which used vegetable oil-based MQL demonstrated a lower friction coefficient and surface roughness due to its superior lubrication property [10]. Soepangkat et al. [11, 12] investigated surface roughness, grinding forces, and chip formation in the surface grinding process of SKD 11 and SKD 61 tool steel using dry and MQL methods. Several parameters that can be used to determine the efficiency of the grinding process are the magnitude of the specific grinding energy, grinding force, the frictional coefficient, and surface micro-crack. The important input variables connected to the efficiency of the grinding process are grinding wheel specification, grinding speed, \( V_f \), doc, and workpiece characteristics [13].

In this study, the analysis is focused on the effect of dry and MQL lubrication methods on the frictional coefficient and surface roughness in surface grinding of SKD 11 tool steel. The frictional coefficient is expressed as the ratio of tangential and normal forces and can be used to measure the effect of lubrication in the grinding zone. Surface roughness is commonly used as a criterion for assessing machinability and surface micro crack is also considered as one aspect of surface integrity.

2. Experimental Procedure

The material used in this experimental work was SKD 11, which is frequently utilized in various areas of manufacturing such as plastic injection mold, hot shear blades, stamping dies, punches, pressure die casting dies, and extrusion tools. SKD 11 possesses an excellent combination of high toughness, wear resistance, compressive strength, and resistance to thermal fatigue cracking. The hardness of this experimental work was 35 HRC. Each ground sample had length of 40 mm, width of 10 mm, and thickness of 5 mm. The experimental conditions of surface grinding experiments and levels of the surface grinding parameters or controllable factors are shown in Tables 1 and 2. The experiments were conducted using 2 CM x 3 Vf x 3 doc factorial design of experiments and replicated thrice. Therefore, the total number of experiments was 36. The order of experiments was also completely randomized. The measured responses were a normal force, tangential force, and surface roughness. These responses were measured after the fifth passes. Kistler dynamometer type 9272 was utilized to measure the two forces, while Mitutoyo surftest SJ-310 was used to measure surface roughness.
### Table 1. Experimental conditions of surface grinding experiments

| Parameter                  | Value                                      |
|----------------------------|--------------------------------------------|
| Workpiece material         | SKD 11                                     |
| Grinding mode              | Plunge surface grinding, up cut            |
| Grinding wheel             | Al₂O₃(A46K)                                 |
| Grinding machine, type     | Krisbow surface grinding, KGS818AH         |
| MQL equipment              | Type SMC mist spray unit LMU 100-15; flow rate 200 ml/h; air pressure 6 bar; nozzle distance 15 mm; nozzle angle 12° |
| MQL coolant                | Palm oil                                   |
| Wheel speed ($V_s$)        | 27.5 m/s                                   |
| Dresser                    | One-point diamond dresser                  |
| Dressing depth             | Total depth of dressing = 0.03 mm          |

### Table 2. The levels of the surface grinding variables

| Cooling Method (CM) | Level | Workpiece speed ($V_f$) [mm/s] | Depth of cut (doc) [mm] |
|---------------------|-------|-------------------------------|------------------------|
| MQL (CM #1)         | Low   | 150                           | 0.01                   |
|                     | Medium| 200                           | 0.03                   |
|                     | High  | 250                           | 0.06                   |
| Dry (CM #2)         | Low   | 150                           | 0.01                   |
|                     | Medium| 200                           | 0.03                   |
|                     | High  | 250                           | 0.06                   |

### 3. Result and Discussions

#### 3.1 Experimental Results

Figure 1 shows the measured FC as the results of the combination of $V_f$ and doc using MQL and Dry during the surface grinding process. The measured SR as the results of the same process are depicted in Figure 2. The analysis of the effect of CM, $V_f$, and doc on FC and SR was performed by applying the regression analysis.

![Figure 1. Measured FC as the results of the combination of $V_f$ and doc using MQL and DRY](image-url)
3.2 Modeling of the responses and the effects of process parameters

FC, SR, and SCD were modelled as a function of CM, Vf, and doc. The mathematical model of FC and SR are expressed in the non-linear form or power function derived from Taylor’s tool life equation \((VT^n C \text{ or } T = CV^{1/n})\) as follows:

\[
Y = C \cdot CM^m \cdot V_f^n \cdot \text{doc}^p
\]  

(1)

The mathematical models formulated in this study are as follows:

\[
\begin{align*}
FC &= C_1 \cdot CM^m \cdot V_f^n \cdot \text{doc}^p_1 \\
SR &= C_2 \cdot CM^m \cdot V_f^n \cdot \text{doc}^p_2
\end{align*}
\]

(2) \hspace{1cm} (3)

The logarithmic transformation of equation (1) is:

\[
\log Y = \log C + m \log CM + n \log V_f + p \log \text{doc}
\]

(4)

The constants and parameters \(C\), \(m\), \(n\), and \(p\) can then be solved by using multiple regression analysis.

3.2.1 Frictional Coefficient Model

The analysis of variance (ANOVA) of the FC model is shown in Table 3, while its analysis of coefficients is presented in Table 4. The R-sq value of 89.3% indicated that 89.3% of the variability in FC was explained by the model with parameters of CM, Vf, and doc. The level of statistical significance used in the regression analysis was 5%. Hence, it can be concluded from Table 3 that regression was significant, while lack-of-fit was not significant. Table 4 shows that all the coefficients of parameters (CM, Vf, and doc) were significant. The variance inflation factors (VIF) values for all parameters were equal to one, which indicated that there was not any multicollinearity in the model. The residuals or error were normally distributed as shown in Figure 3. Therefore, the FC model is valid to represent the relationship between FC and parameters CM, Vf, and doc. The FC model can be expressed as:

\[
FC = 0.225 \cdot CM^{0.174} \cdot V_f^{0.163} \cdot \text{doc}^{0.0689}
\]

(5)
### Table 3. ANOVA table of the regression analysis for the FC model

| Source          | Deg. of freedom | Sum of Squares | Mean Square | F-value | P-value | Significant       |
|-----------------|-----------------|----------------|-------------|---------|---------|-------------------|
| Regression      | 3               | 0.05026        | 0.016752    | 89.11   | 0.000   | Sig. at 5%        |
| Residual        | 32              | 0.00601        | 0.000188    | 1.18    | 0.155   | Not sig. at 5%    |
| Lack of Fit     | 14              | 0.00287        | 0.000205    | 1.18    | 0.155   | Not sig. at 5%    |
| Pure Error      | 18              | 0.00314        | 0.000174    | 1.18    | 0.155   | Not sig. at 5%    |
| Total           | 35              |                |             |         |         |                   |

$S = 0.0137$  
$R^2$ = 89.3%  
$R^2$ (adj) = 88.3%

### Table 4. Analysis of the coefficients for the FC model

| Predictor | Coef  | SE Coef | T      | P-value | Significant | VIF |
|-----------|-------|---------|--------|---------|-------------|-----|
| Constant  | -0.64654 | 0.05882 | -10.99 | 0.000   | at 5%       | 1   |
| log CM    | 0.17437  | 0.01518 | 11.49  | 0.000   | at 5%       | 1   |
| log $V_t$ | 0.16325  | 0.02515 | 6.49   | 0.000   | at 5%       | 1   |
| log $a$   | 0.06891  | 0.00713 | 9.67   | 0.000   | at 5%       | 1   |

The FC model shows that CM had the greatest effect, followed by $V_t$ and doc. The increase of both $V_t$ and doc would increase FC. Figure 4 depicts the effect of CM, $V_t$ and doc on FC. It can be seen that MQL grinding yielded lower FC compared to dry grinding. The reduction of FC reflected the more effective lubrication between the workpiece and the abrasive grinding wheel. During MQL grinding, a small quantity of oil-mist droplets that act as cutting fluid with high speed efficiently penetrates the wheel grain-workpiece interface. This effective penetration of oil-mist droplets creates a durable lubricant tribofilm with lower shearing strength than the base metal, which lowers the tangential force in the grinding process, as well as FC. The increase of $V_t$ and doc cause the enlargement of maximum uncut chip thickness, which in turn would increase FC. Those phenomena were also observed by [15, 16, and 17].
3.2.2 Surface Roughness Model

Previous studies by Adibi et al. [16] stated that the doc had an only marginal effect on SR during the surface grinding process. Therefore, doc was not included in the SCD model. Table 5 shows ANOVA of the surface roughness (SR) model, while its analysis of coefficients is presented in Table 6. The R-sq value of 98.5% indicated that 98.5% of the variability in SR was explained by the model with parameters of CM and Vf. By applying a significance level of 5%, it can be seen in Table 5 that regression was significant, while lack-of-fit was not significant. Table 6 shows that the coefficients of parameters of CM and Vf were significant. Based on the variance inflation factors (VIF) values for CM and Vf were equal to one, which indicated that there was not any multicollinearity in the model. The residuals or errors were normally distributed as shown in Figure 5. Therefore, the SR model is valid to represent the relationship between SR and parameters CM and Vf.

**Table 5.** ANOVA table of the regression analysis for the SR model

| Source         | Deg. of freedom | Sum of Squares | Mean Square | F-value | P-value | Significant |
|----------------|-----------------|---------------|-------------|---------|---------|-------------|
| Regression     | 2               | 0.27006       | 0.135030    | 1125.25 | 0.000   | Sig. at 5%  |
| Residual       | 33              | 0.00410       | 0.000120    |         |         |             |
| Lack of Fit    | 3               | 0.00053       | 0.000177    | 1.48    | 0.115   | Not sig. at 5% |
| Pure Error     | 30              | 0.00357       | 0.000119    |         |         |             |
| Total          | 35              | 0.27416       |             |         |         |             |

R-Sq = 98.5% R-Sq (adj) = 98.4%

**Table 6.** Analysis of the coefficients for the SR model

| Predictor | Coef   | SE Coef | T      | P-value | Significant | VIF |
|-----------|--------|---------|--------|---------|-------------|-----|
| Constant  | -1.01603 | 0.04697 | -21.63 | 0.000   | at 5%       |     |
| log CM    | 0.53701 | 0.01235 | 43.49  | 0.000   | at 5%       | 1   |
| log Vf    | 0.34270 | 0.02047 | 16.75  | 0.000   | at 5%       | 1   |
The SR model can be expressed as:

$$SR = 0.095 \text{CM}^{0.537} \text{V}_f^{0.343}$$

The SR model shows that CM had the greatest effect on SR. Figure 6 reveals that MQL yielded in a smaller value of surface roughness compared to dry conditions. In MQL and dry grinding, the increases in $V_f$ would increase surface roughness. Abrasive grain size, dressing condition, lubricating and cooling effects, and also material removal rate gave a substantial effect on the surface roughness of the machined part. As has been stated, the MQL technique provides a precise flow and effective lubrication in the cutting zone. The increase in the lubrication effect would increase the elastic-plastic deformation beneath the cutting edge of the abrasive grain and lower the workpiece surface roughness. On the other side, increasing $V_f$ would enlarge the maximum uncut chip thickness and results in higher workpiece surface roughness. A similar result was also observed by [13, 15]. The removal of material in MQL grinding is different from other machining processes since mostly caused by shearing and fracturing, which is beneficial in retaining grit sharpness. In dry grinding, the removal of material is caused by high rubbing and ploughing action due to the lack of lubrication. As a result, the workpiece surface resulted from MQL grinding has a narrow gap compared to dry grinding which is shown in Figure 7, which helps to create a lower surface roughness.

![Figure 5. Normal probability plot for SR residuals](image)

![Figure 6. The effects of CM and $V_f$ on SR](image)
Figure 7. Surface morphology obtained by using SEM after (a) MQL grinding and (b) Dry grinding

4. Conclusions
The results of investigation of frictional coefficient and surface roughness in surface grinding of SKD 11 tool steel using MQL and dry techniques are as follows:

- The application MQL could decrease FC and SR significantly because it gives adequate lubrication around the grinding wheel which creates better slipping of the grain in the wheel grain-workpiece interface.
- The decrease of depth of cut and workpiece speed could lessen the maximum uncut chip thickness, which in turn would lower FC as well as SR.
- The application of the MQL technique along with low workpiece speed would yield a lower SR.

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