Effect of Some Thermodynamic Properties of Cutting Fluids on Machinability of Carbon Steel

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Abstract- Cutting fluids are used to reduce heat generated during machining, however some have been discovered to pose health challenges hence the search for viable alternatives. In this paper, three machining conditions (dry machining, wet machining with soluble oil and wet machining with used-engine oil) were conducted on high carbon steel, with a sole aim of investigating the suitability of engine oil as an alternative to soluble oil. Measurements related to effective use of oil as a metal cutting fluids were determined and the machining parameters used were cutting speed (750 – 1750 rpm), feed rate (40 – 120 mm/rev), and depth of cut (0.1 – 0.3 mm). The experimental procedure was formulated using Minitab software version 18 and the machining responses investigated were maximum temperature at the cutting interface, surface roughness, and tool wear rate (TWR). Thermodynamic properties investigated include, flashpoint, specific heat capacity, viscosity and density. The experimental results showed that cutting temperature reduced from an average of 440°C during dry machining to 369.8°C (16% improvement) during machining with used-engine oil and 362.6°C (18% improvement) during machining with soluble oil. The surface roughness produced was generally higher while machining with used-engine oil with an average improvement of 39% in surface integrity. However, when soluble oil was used as cutting fluid, average improvement in surface integrity increased to 70%. Hence, used-engine oil offered impressive lubricating and cooling properties and could replace soluble oil as a cutting fluid during machining.

Keywords- Cutting Fluid, Cutting Speed, Machining, Surface Roughness, Tool Wear

1 INTRODUCTION

Machining parameters play important roles in heat generation during machining processes; among them, cutting speed is the dominant one followed by feed and depth of cut (Kishawoy and Hosseini, 2019). The heat generation in machining as a result of plastic deformation and friction which adversely affect on the life of cutting tools and the quality of the machined parts (Amulya et al., 2016; Silva et al., 2017; Gosai and Bhavsar, 2016). In order to minimize heat during machining, researchers have been exploring methods such as; selection of optimum machining parameters, dry machining with coated cutting tools, and application of cutting fluids (Çakir et al., 2007).

Jamil et al. (2019) worked on influence of cryogenic CO2- and hybrid nanofluid–based minimum quantity lubrication (MQL) techniques for turning Ti–6Al–4V. The used hybrid nanofluid is alumina (Al2O3) with multi-walled carbon nanotubes (MWCNTs) dispersed in vegetable oil. The variables were cutting speed, feed rate, and cooling technique. Results showed that the hybrid nadoadditivates reduced the average surface roughness by 8.72%, cutting force by 11.8%, and increased the tool life by 23% in comparison with the cryogenic cooling.

While qualities of both workpiece and coolants were the focus of Jamil et al. (2019) and Tahmasebi et al. (2019), Hoyne et al. (2015) focused mainly on cutting temperature measurement during titanium machining with an Atomization-based Cutting Fluid (ACF) spray system. They concluded that the ACF spray system with mixture of air-CO2 exhibited superior cooling than flood cooling.

Heat, to some extent can facilitate the cutting process by softening the workpiece, its adverse effects on the other aspects of the process call for better control (Amrita & Krishna, 2014). Therefore, the need to study the effects of some properties of cutting fluids (soluble oil and used-engine oil) on machining characteristics of workpiece in other to determine their effectiveness and suitability in a particular machining process.

2 EXPERIMENTATION

2.1 MATERIALS AND METHODS

The materials used are carbon steel (CS), soluble oil (5% oil and 95% water), and used-engine oil. The chemical compositions of these materials (Tables 1, 2 and 3) were determined using Ametek SPECTROMAX-X metal analyzer model (MAXx-LMM05) and Gas Chromatography–Mass Spectrometry (GC–MS) analyze the physico-chemical properties (flashpoint, specific heat capacity, viscosity, density and pH value) were also determined.

2.2 DETERMINATION OF PHYSICO-CHEMICAL PROPERTIES

2.2.1 Flashpoint/ Specific Heat Measurements

The flashpoint for the cutting fluids was established by fire point tester apparatus. The initial temperature of the sample was recorded. The sample, then put inside the calorimeter with ignition and a stirrer to distribute the energy supplied. Burning of the cutting fluid samples were burned at a pressure of 2500 kN/m².

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### Table 1. Chemical Composition of the Workpiece

| Chemical | C  | Si  | Mn  | P   | S   | Cr  | Mo  | Ni  | Cu  | Fe  |
|----------|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| % wt.    |    |     |     |     |     |     |     |     |     |     |
| 1 Hexane | 0.840 | 0.510 | 0.650 | 0.032 | 0.045 | 0.054 | 0.022 | 0.024 | 0.060 | 98.070 |
| 2 Naphthalene |    |     |     |     |     |     |     |     |     |     |
| 3 Decane |    |     |     |     |     |     |     |     |     |     |
| 4 Naphthalene |    |     |     |     |     |     |     |     |     |     |
| 5 Octane |    |     |     |     |     |     |     |     |     |     |
| 6 Pentadecane |    |     |     |     |     |     |     |     |     |     |
| 7 Hexadecane |    |     |     |     |     |     |     |     |     |     |
| 8 Nonadecane |    |     |     |     |     |     |     |     |     |     |
| 9 Hexacosane |    |     |     |     |     |     |     |     |     |     |
| 10 Hexadecane, |    |     |     |     |     |     |     |     |     |     |
| 11 Heptacosane, |    |     |     |     |     |     |     |     |     |     |
| 12 10-Methylnonadecane |    |     |     |     |     |     |     |     |     |     |
| 13 Eicosane |    |     |     |     |     |     |     |     |     |     |
| 14 1-Octadecene |    |     |     |     |     |     |     |     |     |     |
| 15 Nonadecane, |    |     |     |     |     |     |     |     |     |     |

**2.2.2 Viscosity, Density and pH measurements**

The viscosity of the two cutting fluids was calculated according to Wilke et al, 1994, the kinematic viscosity and density of the two cutting fluids were evaluated by Equations (1) and (2).

\[ \mu = C \times T \]  
\[ \rho = \frac{m_2 - m_1}{V} \]

Where \( \mu \) = Viscosity, 
\( C \) = Glass capillarity constant, 
\( T \) = average flow time 
\( \rho \) = Density 
\( m_2 \) = Mass of density bottle with cutting fluid sample 
\( m_1 \) = Mass of empty density bottle 
\( V \) = Volume of density bottle

### Table 2. Compositional Analysis of Used Engine Oil

| S/N | Component       | Function                          | % Vol. |
|-----|----------------|-----------------------------------|--------|
| 1   | Hexane         | N/A                               | 0.655  |
| 2   | Naphthalene    | N/A                               | 0.680  |
| 3   | Decane         | N/A                               | 1.345  |
| 4   | Naphthalene    | N/A                               | 0.669  |
| 5   | Octane         | N/A                               | 0.775  |
| 6   | Pentadecane    | N/A                               | 2.970  |
| 7   | Hexadecane     | N/A                               | 5.978  |
| 8   | Nonadecane     | N/A                               | 8.312  |
| 9   | Hexacosane     | Antimicrobial activity            | 13.143 |
| 10  | Hexadecane     | N/A                               | 7.500  |
| 11  | Heptacosane    | Antibacterial, Antifungal Activity| 13.302 |
| 12  | 10-Methylnonadecane | N/A                             | 12.047 |
| 13  | Eicosane       | Antioxidant, Lubricant activity   | 12.536 |
| 14  | 1-Octadecene   | Antioxidant, Antimicrobial,       | 10.726 |
|     |                | Antifungal activity              |        |
| 15  | Nonadecane     | Antioxidant                       | 9.362  |

### Table 3. Compositional Analysis of Soluble Oil

| S/N | Component    | Function        | Percentage Volume |
|-----|--------------|-----------------|-------------------|
| 1   | Fixed Oil    | Base Oil        | 84.86             |
| 2   | Fatty alcohol| Corrosion Inhibitor | 5.63          |
| 3   | Boric Acid   | Lubrication     | 1.96              |
| 4   | Oleic acid   | Emulsification  | 5.56              |
| 5   | Phenol       | Disinfectant    | 1.89              |

### Table 4. Machining Parameters and Levels

| Control Factors | Levels |
|-----------------|--------|
| Cutting speed (rpm) | 750, 1250, 1750 |
| Feed Rate (mm/rev) | 40, 80, 120 |
| Depth of Cut (mm) | 0.1, 0.2, 0.3 |

### Table 5. Orthogonal Array for Experiment

| Turning | Cutting speed (rpm) | Feed Rate (mm/rev) | Depth of Cut (mm) |
|--------|---------------------|--------------------|------------------|
| Run    |                     |                    |                  |
| 1      | 750                 | 40                 | 0.1              |
| 2      | 750                 | 80                 | 0.2              |
| 3      | 750                 | 120                | 0.3              |
| 4      | 1250                | 40                 | 0.2              |
| 5      | 1250                | 80                 | 0.3              |
| 6      | 1250                | 120                | 0.1              |
| 7      | 1750                | 40                 | 0.3              |
| 8      | 1750                | 80                 | 0.1              |
| 9      | 1750                | 120                | 0.2              |

**2.3.2 Temperature Measurement**

A digital thermometer K-type thermocouple with data logger was used to capture the temperature at an interval of 5 seconds and temperatures converted to equivalent values in Kelvin using Equation (3).

\[ T (\degree C) + 273 = T (K) \]  

### Table 6. Machining Parameters and Responses

**2.3.3 Surface Roughness, Ra**

The surface roughness, Ra (µm), of the workpiece was measured using a Surface Profilometer Gauge (SRT-6223).
2.3.4 Tool Wear Rate, TWR
The Tool Wear Rate (flank), TWR (g/min), was estimated using Equation (4) (Jeevamalar & Ramabalan, 2018).

\[ TWR = \frac{W_o - W_i}{T} \text{ g/min} \]  

Where \( W_o \) = Tool weight before turning  
\( W_i \) = Tool weight after turning  
\( T \) = Time taken for run

3 RESULTS AND DISCUSSION
3.1 PHYSICO-CHEMICAL PROPERTIES OF THE TWO CUTTING FLUIDS
Soluble oil has flashpoint of 176°C a value higher than that of used-engine oil with 124°C (Table 6). The increase in flashpoint of soluble oil is as a result of presence of water. Soluble oil has a higher specific heat of 4.006 kJ/kg.K than used-engine oil with 1.603 kJ/kg.K (Table 6). This indicates that soluble oil is capable of absorbing more heat from the cutting zone and will act as a better coolant than used-engine oil.

| S/N | Properties               | Soluble Oil | Used-engine Oil |
|-----|--------------------------|-------------|-----------------|
| 1   | Flash Point (°C)         | 176         | 124             |
| 2   | Specific Heat (kJ/kg.K)  | 4.006       | 1.603           |
| 3   | Viscosity (mm²/s)        | 0.9612      | 54.9806         |
|     | (at 40):                 | 0.3524      | 8.5066          |
|     | (at 100):                | 0.929       | 0.797           |
| 4   | Density (g/cm³)          | 8.3         | 6.4             |
| 5   | pH                       | 6.4         | 6.4             |

Results obtained showed that viscosity of the two cutting fluids decreased with increase in temperature from 40°C to 100°C. The viscosity of used-engine oil was 54.9806 mm²/s and 8.5066 mm²/s at 40°C and 100°C respectively which is higher than that of soluble oil with 0.9612 mm²/s and 0.3524 mm²/s at 40°C and 100°C respectively (Table 6). Since used-engine oil has higher viscosity, it will flow sluggishly to the cutting zone during machining than soluble oil with lower viscosity. Since soluble oil is a denser than used-engine oil (Table 6). Increase in value of density of soluble oil could be as a result of water forming higher percentage of the formulation. The pH value for soluble oil is 8.3. This indicates a base/alkaline cutting fluid. This value falls within the range of pH of most cutting fluids 8.0 and 9.5 (Amrita et al., 2014). Used-engine oil however has pH of 6.4 when measured.

3.2 MACHINING PROCESS RESPONSES
3.2.1 Cutting Temperature
Figure 1 shows temperature against cutting speed for dry machining condition and two cooling conditions (i.e. soluble oil and used-engine oil). It can be seen that temperature at the cutting interface was high during dry machining condition (at average of 440ºK) and this is because there was no coolant used resulting in heat generated by friction between tool and workpiece. The situation improved when soluble oil and used-engine oil were applied as coolant, because heat generated was removed from the cutting interface. However, the cooling condition when soluble oil was applied as coolant improved cutting temperature than when used-engine was used. This could be attributed to higher specific heat capacity of soluble oil than used-engine oil. The result is similar to the work of (Khan et al., 2009).

3.2.2 Surface Roughness, Ra
Figure 2 shows the variation of surface roughness with cutting speed when varying feed rate and depth of cut. It can be seen (Fig. 2) that average surface roughness value during dry machining condition was 4.4 µm. However, there is improvement of 2.7 µm (39%) when machining with used-engine oil. With soluble oil, average surface roughness value of 1.3 µm (70%) was obtained compared to dry machining with 52% improvement with used-engine oil. The higher value in surface roughness for dry machining condition could be as a result of more energy imparted by the tool as against machining using used-engine oil. This is line with Ogedengbe et al. (2018).

The viscosity also contributed to improving the surface roughness since used-engine oil has a high value of viscosity which is an indicative of high resistance to flow so its ability to flow to the cutting zone was less and therefore the roughness produced was high. The result from Harikrishnan et al. (2017) shows similar trend.
3.2.3 Tool Wear Rate, TWR

Figure 3 shows Tool Wear Rate (TWR) against cutting speed for two machining condition. In Figure 3 at 750 rpm cutting speed, there were cases of tool wear only during dry machining condition with values of 0.0017 g/min, 0.002 g/min and 0.0026 g/min in run 1, run 2 and run 3 respectively. Meanwhile when the two cooling conditions were applied, there were no cases of tool wear at this cutting speed. During dry machining condition, friction at the tool-workpiece interface will be high, hence an increase in TWR but as coolants is applied for these runs, the wear ceased during the cutting. The trend is similar to the work of (Krishna et al., 2010).

Fig. 3: Tool Wear Rate (TWR) Versus Cutting Speed

4 CONCLUSIONS

Based on results obtained at the end of these study, it was concluded that average cutting temperature reduced from 440°C during dry machining to 369.8°C representing a 16% improvement during machining with used-engine oil. This temperature further reduced by another 2% to 362.6°C when machining with soluble oil. Hence, cooling property of used-engine oil offered a competitive performance with that of soluble oil and can be used as substitute for cooling purpose during turning. The average surface roughness improved from 4.4 µm during dry machining to 2.7 µm during wet machining with used-engine oil as cutting fluid. This value further improved to 1.3 µm when machining with soluble oil. Although soluble oil produced better surface integrity, yet, used-engine oil performed favorably well too in improving surface finish. Finally, used-engine oil offered superior lubricating property than soluble oil and hence showed better tool wear rate (TWR) results.

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