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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 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 440ºK during dry machining to 369.8ºK (16% improvement) during machining with used-engine oil and 362.6ºK (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 (Kishawy and Hosseini, 2019). The heat generation in machining as a result of plastic deformation and friction which adverse effect 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 (Çakīr *et al.*, 2007).

Jamil *et al.* (2019) worked on influence of cryogenic CO_2 and hybrid nanofluid–based minimum quantity lubrication (MQL) techniques for turning Ti–6Al–4V. The used hybrid nanofluid is alumina (Al_2O_3) 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 nanoadditives 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.
However, in a bid to explore the use of cutting fluid to improve machining processes, Tahmasebi *et al.* (2019) simulated and analyzed experimentally the flow of coolant in cryogenic milling. Their results indicated that pressure in the range of 2 - 4 bar was reliable and ensuring a quality coolant with constant flow rate was crucial for efficient 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-CO_2 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/m^2.

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Table 1. Chemical Composition of the Workpiece

Chemical	C	Si	Mn	P	S	Cr	Mo	Ni	Cu	Fe
% wt.	0.840	0.510	0.650	0.032	0.045	0.054	0.022	0.024	0.060	98.070

Table 2. Compositional Analysis of Used Engine Oil

S/N	Chemical 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, Antifungal activity	10.726
15	Nonadecane,	Antioxidant	9.362

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).

$$\mu = C \times T \tag{1}$$

Where μ = Viscosity,
C = Glass capillarity constant,
T = average flow time

$$\rho = \frac{m_2 - m_1}{V} \tag{2}$$

Where $\rho = Density$
m_2 = Mass of density bottle with cutting fluid sample
m_1 = Mass of empty density bottle
V = Volume of density bottle

Table 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

2.3 Machining Parameters and Responses

2.3.1 Design of Experiment

The experiment was designed using Minitab version 18.0. The three factors selected are cutting speed, feed rate, and depth of cut. Taguchi Method was used to design the experiment with a total of 9 runs. Table 4 and Table 5 show the machining parameters with levels and the L9 orthogonal array respectively. The choice of selected parameters and levels were guided by literature, machine capacity and preliminary trial machining results.

Table 4. Machining Parameters and Levels

Control Factors	Levels		
	1	2	3
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 Run	Cutting speed (rpm)	Feed Rate (mm/rev)	Depth of Cut (mm)
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 capture the temperature at an interval of 5 seconds and temperatures converted to equivalent values in Kelvin using Equation (3).

$$T\,(°C) + 273 = T\,(K) \tag{3}$$

2.3.3 Surface Roughness, Ra

The surface roughness, Ra (µm), of the workpiece was measured using a Surface Profilometer Gauge (SRT-6223).

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2.3.4 Tool Wear Rate, TWR

The Tool Wear Rate (flank), TWR (g/min), was estimated using Equation (4) (Jeevamalar & Ramabalan, 2018).

$$TWR_n = \frac{I_o - I_n}{T}\ g/min \qquad (4)$$

Where I_o = Tool weight before turning
I_n = 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.

Table 6. Physico-chemical Properties of Soluble Oil and 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 (mm^2/s)	0.9612 (at 40); 0.3524 (at 100)	54.9806 (at 40); 8.5066 (at 100)
4	Density (g/cm^3)	0.929	0.797
5	pH	8.3	6.4

Results obtained showed that viscosity of the two cutting fluids decreased with increase in temperature from 40° to 100°C. The viscosity of used-engine oil was 54.9806 mm^2/s and 8.5066 mm^2/s at 40° and 100°C respectively which is higher than that of soluble oil with 0.9612 mm^2/s and 0.3524 mm^2/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 440°K) 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).

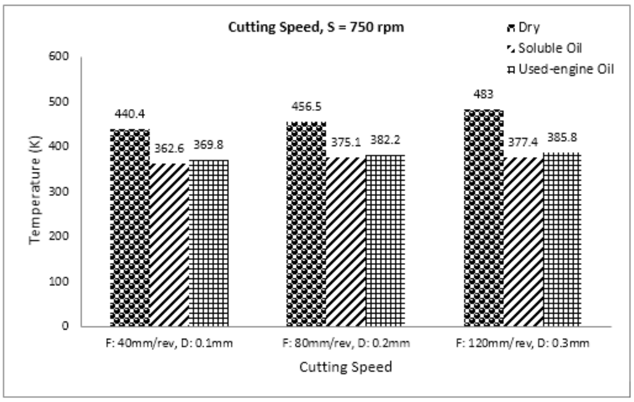

Fig. 1: Temperature Versus Cutting Speed

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.

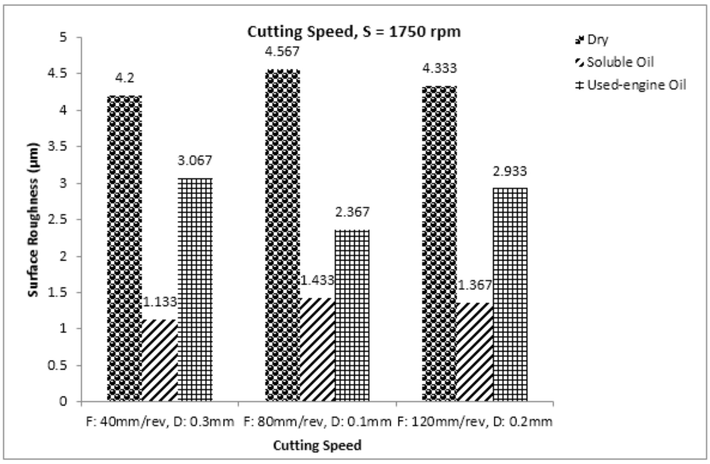

Fig. 2: Surface Roughness (Ra) Versus Cutting Speed

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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).

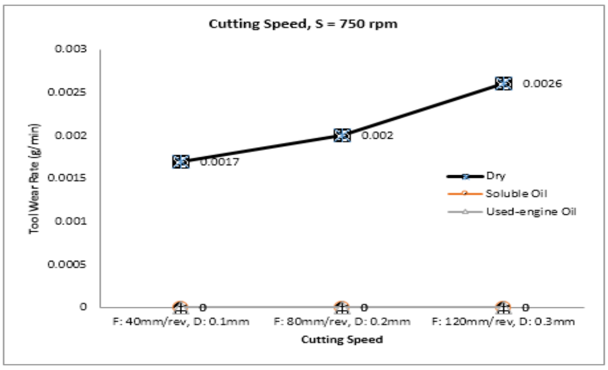

Fig. 3: Tool Wear Rate (TWR) Versus Cutting Speed

4 CONCLUSIONS

Based on results obtained at the end of these study, it was concluded that average cutting temperature reduced from 440°K during dry machining to 369.8°K representing a 16% improvement during machining with used-engine oil. This temperature further reduced by another 2% to 362.6°K 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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