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Research Article

Tool Life in Turning Processes: Effect of Lubricants with a Small Amount of Graphite as Cutting Fluid

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A B S T R A C T

This study aims to determine the effect of various lubricant-based cutting fluid parameters to produce an optimal tool life in turning operations. This research does not use coolant as a cooling fluid, but as a lubricant with the addition of a small amount of graphite (solid lubricant) at a minimum quantity condition. By using HSS cutting tools and a low carbon steel workpiece, an experimental design was carried out using the Taguchi method with three parameters, that is the viscosity of the lubricant, the percentage of graphite in the lubricants, and the supplied pressure of the lubricants. Each parameter is designed to have three levels. The experimental results show that the percentage of graphite in the lubricant has the largest contribution of 52% and the viscosity of the lubricant is 38% while the fluid supplied pressure is only 7% of the tool life. Furthermore, based on the analysis of variance (ANOVA) it is known that the percentage of graphite and viscosity of the lubricant has a significant effect on the cutting tool life. The optimal and longest tool life is achieved when carried out with lubricant SAE20-50 with the percentage addition of 0.10% graphite with a pressure of 5 Bar.

1. INTRODUCTION

During the turning, the metal cutting processes occur as well as chip removal by the lathe cutting tool. Due to the continuous friction between the chips moving on the rake angle of the cutting tool, heat will be generated in the cutting contact area. This cutting heat will cause the accumulation of an increase in tool temperature in the continuous machining process. Excessive cutting temperatures will have a detrimental effect on both the tool and the workpiece by weakening the structural integrity of the two parts in contact. However, 80% of the heat is distributed in the rake face, so the cutting tool will have a bigger effect, namely high wear. The high level of cutting tool wear will affect other machinability indicators such as high cutting forces and low surface quality. To keep the cutting temperature low, it is important to use the cutting fluid in the cutting zone in the right amount [1-2]

The machining mechanism and the cutting fluid are closely related to the heat generated by the friction that occurs between the two surfaces (the tool and the workpiece) that are in relative motion. In such cases, the increase in the deformation rate of the material is related to several factors such as temperature, stress, and material characteristics [3]. Plastic deformation of the workpiece material, as well as friction due to relative motion, contribute to

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heat generation. Generally, there are three zones of the tool-workpiece interface that make a major contribution, as shown in Figure 1 [4].

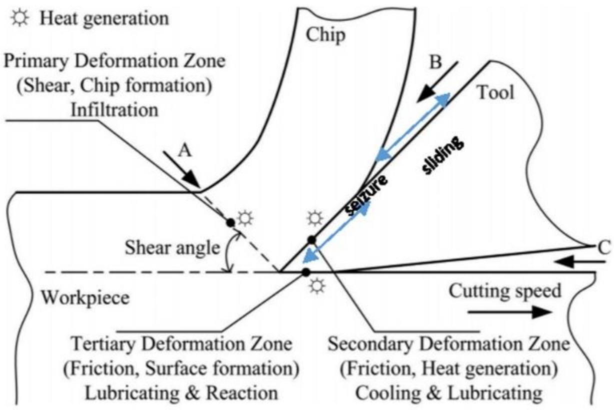

Figure 1. Three deformation zones generated by cutting fluid [4]

The primary deformation zone is the first to be impacted shortly after the chips are formed after being cut off by the cutting tool, which is the internal zone that occurs in the shear plane. The secondary deformation zone is where the tool and chip contact each other (tool-chips interface), and the tertiary deformation is the tool and workpiece contact zone on the main plane of the tool (flank surface). Based on this machining mechanism, cooling is usually applied along lines A, B, and C (Fig. 1) [5]. However, the penetration of coolant in this path is still questioned by some researchers because cutting fluid or coolant may only affect the primary zone but hardly affect the secondary and tertiary zones [6].

Kishawy et al. [7] stated that the coolant had difficulty accessing the flank surface during machining operations or in the seizure zone of the rake surface according to Trent et al [8]. Childs and Rowe [9] also concur that lubrication poses special challenges when accessing the seizure zone in the seizure zone.

The cutting fluid in the cutting processes performs two basic functions, namely cooling and lubrication. The cutting fluid serves as coolant means, that the cutting fluid removes the heat generated from the machining zone, and thus protects the tool and workpieces from overheating. So, the cooling action is based on the heat generated. The cutting fluid as a lubricant means that the cutting fluid serves to reduce the dynamic coefficient of friction between the surface of the rake face area and the chip formed, thereby minimizing the rate of heat generation. Thus, the lubrication mechanism occurs before heat generation occurs, rather than after heat generation as in the case of cooling. In addition to cooling and lubrication, the cutting fluid can also remove chips from the cutting zone [10].

The cooling process is usually carried out using a cutting fluid in the form of a coolant. However, it will be effective in reducing wear on the tool if it is supplied with a very large volume (flood cooling). This will have a negative impact both in terms of production costs and on environmental aspects. Therefore, the use of lubricants can be an alternative because it can reduce the coefficient of friction between the tool and the workpiece. Therefore, it can lower the cutting temperature, thus maintaining a longer tool life. The types of lubricants used in the machining process can be divided into several types, namely fluid lubricants, semi-solid lubricants, and solid lubricants [11].

The properties of solid lubricants are low coefficient and good compressive strength, as well as good adhesion to the substrate surface. Solid lubricants are usually used in the form of a dry powder or as a coating agent. Some examples of solid lubricants include graphite, molybdenum disulfide, boron nitride, tungsten disulfide, and polytetrafluorethylene [12].

The use of solid lubricants can minimize the effect of reducing tool wear and can also improve the surface quality of a product. According to research at Purdue University, graphite is a very thin layer of carbon that has potential uses. Graphite has superior thermal conductivity, and high strength, and provides very low friction [13]. However, graphite can only be applied manually, because of its dense shape so it is not practical to use it efficiently. The mixture of graphite and lubricant can help increase its fluidity, thus providing a solution for practical application. The researcher said that the addition of graphite to lubricating oil resulted in a decrease in the coefficient of friction by 33-36% and also a decrease in temperature by 6-7% compared to using only oil lubricant. The mixture of graphite lathe with water-soluble oil makes it into a paste. In lathe operations, the use of graphite as a solid lubricant can reduce surface roughness by 8-10% [14].

Based on the explanation above, the viscosity of the lubricant plays an important role in the effective use of graphite as a solid lubricant. However, the use of different lubricant viscosities must be accompanied by different pressures, so that graphite can transfer well to the cutting contact area. For this reason, in this study, the characteristics of the lubricants with different viscosities mixed with several variations of the graphite against the tool life were studied. The lubricant pressure factor is also a parameter that is studied for its contribution or effect.

2. METHOD

In this section, several stages are described to be carried out to achieve the research objectives. They include materials and equipment needed in this experimental research. Then an experimental design involving several parameters was carried out using the Taguchi method. The experimental procedure is described at the end of this section.

2.1. Material and Apparatus

To determine the tool life characteristics related to the cutting fluid in the form of lubricant with graphite additive, some experimental materials and equipment are needed. The workpiece material is low-carbon steel (St. 37) with a diameter of 25 mm and a length of 150 mm. This material is often found in the market. While the cutting tool used is an HSS cutting tool for a lathe machine. In this experiment, the lubricant used is lubricating oil sold in the market with different viscosities, namely SAE 10-30, SAE 10-40, and SAE 20-50 (e.g., SAE 10-40 means a viscosity grade of 10 at a low temperature and 40 at a higher temperature). This lubricating oil serves to lubricate the tool and workpiece (to reduce friction) and thereby reduce or stabilize the cutting temperature. An element that is mixed in the lubricating oil is graphite. This is because graphite has a high carbon content which can be expected to reduce the coefficient of friction between the tool and the workpiece as this study will prove. The selected graphite is in the form of powder obtained from the shop as shown in Figure 2. The specifications of the graphite powder are Carbon 98.02%, and the rest are in the form of ash max and moisture with a size of 200 mesh or 74 microns.

Figure 2. Graphite powder as a lubricant additive

The experimental apparatus is a lathe machine tool, compressor, and oil gun. The compressor is used to distribute pressurized lubricant in the machining process. An oil gun is like a shotgun that directs a small volume of graphite-mixed lubricant to the machining processes.

Flank wear [mm] is caused by friction between the flank face of the tool and the machined workpiece surface and leads to loss of the cutting edge. The flank wear measurement uses an optical microscope. This microscope takes pictures on the major flank surface of the cutting tool and the pictures can be magnified up to 100 times for measurement. Flank wear measurement (VB, in mm) is conducted by measuring the flank wear distance for 10 selected points in the pictures. Then to get a flank wear value, an arithmetic average of those measurement values is carried out. The scheme for measuring the cutting tool flank wear can be shown in Figure 3.

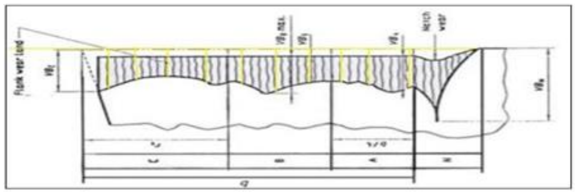

Figure 3. Scheme for measuring flank wear

2.2. Experimental Design

The Taguchi method is used in the experimental design to determine the effect of several factors on tool wear in turning operations.

2.2.1. Quality Characteristic

There are three types of quality characters in the Taguchi experimental method (also called signal-to-noise (SN) ratio), namely smaller is better, nominal the better, and larger the better. The determination of the appropriate quality character is closely related to the purpose of this study. As mentioned in the introduction, the objective of this research is to determine the minimum wear characteristics of the cutting tool in the turning processes for various control factors given. A low tool wear rate indicates good lubrication and cutting fluid quality and the best percentage of graphite additive. Therefore, the selected quality character is “smaller is better”.

2.2.2. Determination of Quality Controlling Factors

As independent parameters in this experiment are 1) the percentage of graphite, 2) the type of lubricant, and 3) the lubricant supplied pressure. Each parameter is designed to have three levels and is denoted as level 1, level 2, and level 3. The response observed in this experiment was flank wear (mm). Parameters of graphite as a lubricant additive varied between 0.05%, 0.08%, and 0.10%. Lubricant uses 3 levels of viscosity, namely SAE 10-30, 10-40, and 20-50. Supply lubricant pressure to machining operations also carried out with the pressure variations of 4, 5, and 6 bar.

In this experimental design, the workpiece material is cylindrical with an initial diameter of 25 mm. The machining process parameters that were kept constants for all experiments were cutting speed (v_c) 30 m/min, feed rate (f) 0.2 mm/rev, and axial depth of cut (a) 1 mm.
The response (flank wear) was measured every 10 mm interval of the cutting length (lt). If it does not meet the flank wear criteria of 0.3 mm, then the cutting process is carried out continuously for another 10 cm and so on.

2.2.3. Orthogonal array matrix selection

The number of rows in the orthogonal array table determines the number of experiments that must be carried out while the number of columns determines the factors that make it up. By using Minitab, an orthogonal array L9 (34) matrix was chosen, where the experiment was carried out 9 times, but with 3 replications for each combination. So a total of 27 experiments were carried out.

2.3. Experimental Procedure

To obtain flank wear data, a series of turning operations with cutting fluid using lubricants mixed with a small amount of graphite were carried out. Then a series of tool wear measurements are conducted.

2.3.1. Turning operation and lubrication

First, preparation of the cutting tool and the workpiece is used. Then preparations are made for pressurized lubrication with a minimum quantity. For this lubrication, an oil gun with a compressor is connected and placed on the part where the cutting process occurs. A mixture of lubricants of various types and percentages of graphite is filled with the oil gun. The flow of lubricant out of the nozzle can be adjusted by turning the oil gun valve. After the workpiece is attached to the lathe, the machining process is carried out with the same spindle rotation (rpm), cutting speed (v_c), feed rate (f), and depth of cut (a). The cutting operations were made 10 cm long, then the flank wear measurements were taken. If the flank wear has not reached the minimum limit of 0.3 mm, then cutting along the 10 cm long cut interval continues.

2.3.2. Tool wear measurement

The tool used in the 10 cm long cutting process will be viewed on an optical microscope to measure the wear of the flank surface. The cutting tool is placed on the optical microscope table and the surface of the main cutting eye is positioned perpendicular to the lens on the optical microscope, then an image is taken. After the image of the tool is obtained, then it is measured using image processing software to see the wear of the tool as shown in Figure 3

2.4. Data Processing

The data obtained directly in the experiment are a) tool wear (mm), when it slightly exceeds the 0.3 mm tool wear limit, and b) the length of cutting that has been made to reach the wear limit. The cutting length (l_t) is an interval of multiples of 100 mm (e.g.: l_t = 400 mm when tool wear of 0.3 mm is reached). For the response value in the form of wear rate (mm/min), then the cutting time, t_c of all intervals multiples of 100 mm must be known. This cutting time (min) can be measured by equation (1),

$$t_c = v_f / l_t \text{ .... (1)}$$

so that the wear rate of the cutting tool (mm/min) can be determined by using equation (2),

$$wear\ rate\ = \frac{tool\ wear}{t_c} \text{ ...(2)}$$

Wear rate [mm/min] is data that is the result of observations that will be analyzed further

3. RESULT AND DISCUSSION

3.1. Result

Tool wear data is collected every 100 mm of cutting length. The experiment was stopped when the average flank wear limit of 0.3 mm was reached. The result of the flank wear (mm) is obtained by measuring the image taken from the optical microscope as shown in Figure 4.

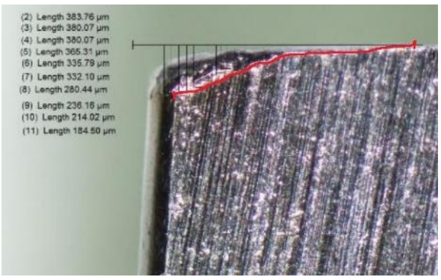

Figure 4. Flank wear in the lathe turning tool

Tool life (in minutes) up to an average wear limit up to 0.3 mm is determined according to the data processing procedure in section 2.4. From these two parameters, the tool wear rate (mm/min) was obtained for twenty-seven experiments with three replications for each level parameter as shown in Table 1.

This table shows that each combination of graphite percentage, type of lubricant, and supplied pressure gives different tool wear rates. Although it provides different tool wear rates, what gives the lowest wear rate is the combination of an SAE 20-50 lubricant mixture with an additional 0.1% graphite supplied with a pressure of 5 Bar. Meanwhile, the one that provides the highest wear rate is the combination of an SAE 10-30 lubricant mixture with an additional 0.05% graphite and a distribution pressure of 4 Bar.

Table 1. Wear rate as a response in the Taguchi method

No	Parameter level			Wear rate (mm/min)
	Graphite (%)	Lubricant	Pressure (bar)	
1	0,05	SAE10-30	4	0,03873
2	0,05	SAE10-30	4	0,04395
3	0,05	SAE10-30	4	0,03275
4	0,05	SAE10-40	5	0,02397
5	0,05	SAE10-40	5	0,02664
6	0,05	SAE10-40	5	0,02801
7	0,05	SAE20-50	6	0,01600
8	0,05	SAE20-50	6	0,02278
9	0,05	SAE20-50	6	0,02420
10	0,08	SAE10-30	5	0,01784
11	0,08	SAE10-30	5	0,03170
12	0,08	SAE10-30	5	0,02703
13	0,08	SAE10-40	6	0,01673
14	0,08	SAE10-40	6	0,02388
15	0,08	SAE10-40	6	0,01921
16	0,08	SAE20-50	4	0,01431
17	0,08	SAE20-50	4	0,02009
18	0,08	SAE20-50	4	0,02239
19	0,1	SAE10-30	6	0,01774
20	0,1	SAE10-30	6	0,01912
21	0,1	SAE10-30	6	0,02251
22	0,1	SAE10-40	4	0,01509
23	0,1	SAE10-40	4	0,01707
24	0,1	SAE10-40	4	0,01592
25	0,1	SAE20-50	5	0,01371
26	0,1	SAE20-50	5	0,01548
27	0,1	SAE20-50	5	0,01822

The experimental results as shown in Table 2, show that each combination of graphite percentage, type of lubricant, and distribution pressure gives a different level of tool wear. Although they provide different levels of tool wear, the one that provides the lowest tool wear is the combination of the SAE 20-50 lubricant mixture with the addition of 0.1% graphite supplied with a pressure of 5 Bar. Meanwhile, the one that gives the highest tool wear is the combination of a mixture of SAE 10-30 lubricant with an additional 0.05% graphite supplied with a pressure of 4 Bar.

However, it is not clear from Table 2 which factors contribute the most to the tool wear. Therefore, the results obtained were analyzed using the Signal-to-Noise Ratios (S/N Ratios) method with the smaller is the better approach.

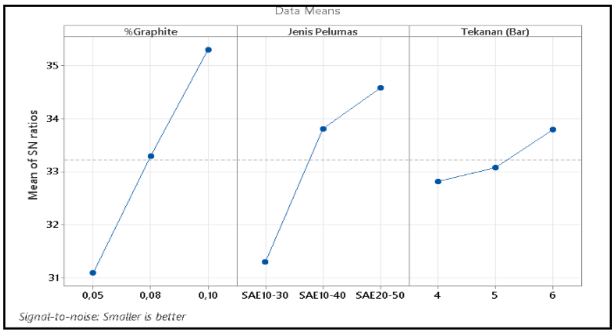

Figure 5. S/N Ratios analysis to see the factors that contribute to the wear rate

The results of the analysis of S/N Ratios in Figure 5 show that the percentage of graphite and the type of lubricant shows a sharp slope of the graph compared to the lubricant supplied pressure. Therefore, qualitatively the percentage of graphite and the type of lubricant contributed more to the tool wear.

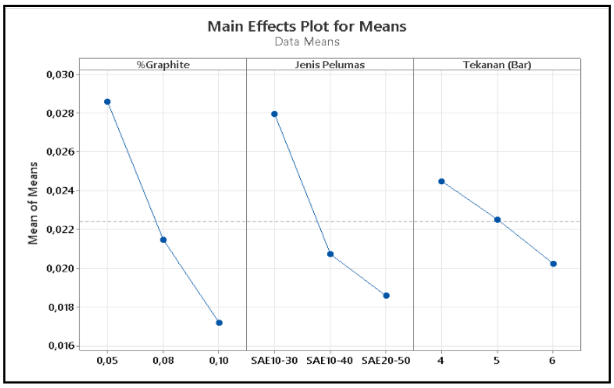

Figure 6. Main effect plot for means

Furthermore, the main effect plot for means as shown in Figure 6 is used to determine the relationship between factors and responses more clearly than the results of the previous S/N Ratios analysis. From this figure, the higher the percentage of graphite, the viscosity of the lubricant, and the pressure used, the lower the flank wear rate will be. Tool lubrication by using a mixture of SAE 20-50 with the addition of 0.1% graphite and supplied with a pressure of 6 Bar is the optimal choice to reduce the flank wear rate of the tool.

However, the results of this analysis have not been able to conclusively provide an overview of the overall effect of the tested parameters. Although the slope value of the influence of the pressure variation factor with the analysis of S/N Ratios is small, it is still possible to provide a significant difference in the overall tool wear rate. For this reason, it is necessary to carry out further statistical analysis to determine whether the three parameters above have a significant effect on the rate of tool wear. Using the 95% confidence level (α=5%), an analysis of variance (ANOVA) using the Minitab statistical software was performed. The results are shown in Table 2.

Table 2. Analysis of variance (ANOVA)

Sources	DF	Adj SS	Adj MS	F-value	p-value	Contribution
Graphite	2	0,000592	0,000296	15,97	0,000	51,8%
Lubricant	2	0,000432	0,000216	11,65	0,000	37,8%
Pressure	2	0,000081	0,000040	2,18	0,139	7,0%
Error	20	0,000371	0,000019			3,3%
Lack-of-Fit	2	0,000076	0,000038	2,33	0,126	
Pure Error	18	0,000295	0,000016			
Total	26	0,001476				

From the ANOVA as shown in Table 3, it is known that the percentage of graphite and the type of lubricant have a p-value <0.05 so these two parameters have a significant effect on the tool wear rate. On the other hand, the lubricant supplied pressure has a p-value > 0.05 (0.139). This value shows that this parameter does not have a significant effect on the tool wear rate.

3.2. *Discussion*

Graphite is a solid powder material so its penetration in the contact area of the tool and the workpiece in the turning process to produce an effective lubricating effect is quite difficult. Therefore, graphite which has the potential to reduce friction must be mixed with a lubricant so the effect can reach the contact area. Because the mineral lubricants have different viscosities, the distribution pressure must be considered also [15]. In addition, the lubricant variation also aims to see the possibility that the viscosity of the lubricant plays a more important role in reducing friction

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compared to the addition of a small amount of graphite.

As the percentage of graphite increases in higher viscosity lubricants, this mixture greatly reduces friction and reduces tool wear. So that the viscosity factor of the lubricant used also has a significant effect in reducing the rate of tool wear. In their research, Rao and Krishna also proved this, where using a larger percentage of graphite, but using only one type of lubricating oil did not have much effect on tool wear [14]. Therefore, the combination of graphite percentage with varying viscosity of lubricating oil will further increase the effectiveness of graphite as a lubricant in a machining process.

According to Rao and Krishna [14], graphite also can increase the shear resistance, because graphite will form more and more films. This is because graphite is composed of planes of polycyclic carbon atoms that have a hexagonal orientation. As a result, the distance between the carbon atoms becomes longer, weakening the bond. In the application in areas that have high temperatures such as the machining process, this condition will increase the opportunity for the formation of more films.

Graphite as a solid material has disadvantages in its distribution, especially if the process takes place continuously. Therefore, a small amount of graphite with minimal lubrication will make a significant contribution to the observed response. The use of lubricants with a certain viscosity, especially those with high viscosity, needs to be supported by choosing the right distribution pressure. This is because the higher the viscosity, the higher the pressure is required [16].

So based on the results of this study where the optimal use of graphite must use a lubricant with high viscosity that ignores the variation of the applied pressure which will make it difficult to reach the contact area, especially the sticky zone in the machining process. So based on the results of this study, the optimal addition of graphite also uses a lubricant with high viscosity that ignores the variation of the applied pressure. This results in increased difficulty in reaching the contact area, especially the sticky zone in the machining process. Therefore, perhaps a small amount of graphite should not be mixed with lubricant but can be mixed with coolant-based water so that the effect of pressure can be ignored and at the same time it can be used as a medium to distribute graphite to the contact area between the tool and the workpiece.

4. CONCLUSION

This research has studied the tool life in the turning operation related to the cooling process using several parameters e.g. lubricant viscosities, percentage of graphite additive, and supplied lubricant pressure. By using the Taguchi experimental design method, it was concluded that the addition of a small amount of graphite had a contribution to tool life of 51.8%, much larger than that of the lubricant itself of 37.8%. Meanwhile, the lubricant distribution pressure parameter only contributes 7.0% to the tool wear rate. Using the 95% confidence level (α=5%), the ANOVA results showed that the graphite and the viscosity of the lubricant had a significant effect on the rate of tool wear while maintaining a longer tool life. The tool cooling parameter that gives the optimal value (long tool life) is a cutting fluid with lubricant SAE 20-50 mixed with 0.10% graphite and supplied pressure of 5 Bar.

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