EXPERIMENTAL EVALUATION OF A BIO-BASED CUTTING FLUID USING MULTIPLE MACHINING CHARACTERISTICS

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Abstract

In this paper, the authors present a study that was conducted in an undergraduate research program using experimental tests to evaluate the effectiveness of a soybean-based cutting fluid applied in CNC turning operations. Using two machining performance characteristics, namely surface roughness and tool wear, the study tested the effects of a soybean-based cutting fluid on improving surface finish and reducing tool wear compared to a petroleum-based cutting fluid when high-carbon alloy steel was machined. A statistical analysis of the data indicated that the bio-based cutting fluid performed as well as the petroleum product in terms of surface finish, and significantly better than the petroleum-based cutting fluid in terms of controlling tool wear. These positive test results may provide supporting evidence to manufacturing professionals for making strategic machining decisions regarding the choice of cutting fluids.

Introduction and Literature Review

Cutting fluids are used extensively in metal machining processes to remove and reduce heat during machining operations. On one hand, the use of cutting fluids greatly enhances machining quality while simultaneously reducing the cost of machining by extending tool life [1]. The use of petroleum-based cutting fluids, however, has been found to affect operators, causing medical problems such as dermatitis, while the disposal of the fluids needs to follow special provisions to take care of the environmental impact. With pressure from global climate change, environmental protection, natural resource limitation and governmental regulations, green manufacturing is gradually becoming a philosophy [2], [3]. The cost of machining, environmental impact, and operators' health concerns have driven researchers to find equivalent dry-cutting conditions that could satisfy machining requirements without the use of cutting fluids [4], [5]. Because of the very nature of machining processes, studies conducted by Diniz & Oliveira [4] and Khan & Dhar [5] concluded that machining under wet conditions was still better for tool life, and dry cutting would be of limited use in cases where the depth of cut is shallow.

There are a large number of cutting fluids that have been developed and formulated from organic and inorganic materials. Although cutting fluids are generally useful, their effectiveness in a given application may vary due to workpiece material and tool material properties, along with different machining conditions and whether a cooling or lubricating mechanism is predominant. The majority of the existing cutting fluids are petroleum-based products, which are hazardous for storage and disposal [6]. Particularly, the petroleum-based cutting fluids are environmentally more difficult to handle compared with bio-based emulsions. Before disposal, special physical or chemical treatment techniques may be needed to remove hazardous components from the used cutting fluids by an EPA-permitted hazardous waste management agency. Studies have shown that statistically significant increases in several types of cancer as well as an increased risk of respiratory irritation or illness are due to prolonged exposure to cutting fluid mists [7], [8]. Thus, it would be beneficial for manufacturing applications to use lesser amounts of petroleum-based cutting fluids.

In recent times, alternative cutting fluids based on vegetable oils have been explored for machining operations [9], [10]. Due to their relatively low flash point (about 420°F), when petroleum-based cutting fluids are used, the heat at the workpiece-cutter interface often generates a mist, which is harmful to machine operators [11]. Flash point is the lowest temperature at which a liquid can form an ignitable mixture in air near the surface of the liquid. The lower the flash point, the easier it is to ignite the material. Having a high molecular weight (flash point of around 600°F), the soybean-based cutting fluids greatly reduce the chance of mist generation in machining processes. In addition, it has been reported that these soy-based cutting fluids have a very high film strength, which helps to lubricate the cutting-tool/work-piece interface, thereby reducing heat generated and tool wear [12], [13].

Though the bio-based cutting fluids have been available on the market for some time, there is not widespread use of them in industry. A limited number of studies on bio-based cutting fluids have been reported in the literature, which focused on specific cutting-fluid products [14-17]. For example, the studies by Belluco & DeChiffre's [14], [15] focused specifically on the performance of formulated oils blended with rapeseed oil, ester oil, and sulfur and phosphor additives used in drilling AISI 316L austenitic stainless steel. Their experimental data indicated that the bio-based fluids performed better than the mineral-oil-based products in terms of prolonged tool life, better chip breaking, lower tool wear, and lower cutting forces. Because bio-based cutting fluids can be formulated from different agricultural products, it is hard to make a general conclusion due to the bio-product diversity.

In this study, the cutting fluid was a soybean-based oil uniquely formulated through an engineered approach to increase oxidative stability of the soybean oil [18]. An improved understanding of the soybean-based cutting fluid through scientific evaluation will help manufacturing professionals recognize the benefits of this cutting fluid, and will better prepare them for making strategic machining decisions regarding the choice of cutting fluid.

Research Questions

The goal of this study, then, was to compare the effectiveness of a soybean-based cutting fluid with its petroleum alternate when used in CNC turning operations in order to evaluate their impact on the quality characteristics of the parts being turned. Different turning characteristics, namely surface roughness, tool life/tool wear, material removal rate, cutting force, machining vibration, etc., have been used in other studies to evaluate machining performance. Surface roughness is an important quality measurement of machined parts, and tool wear plays a critical role in determining the part quality and the machining cost. These two characteristics can be relatively easily measured in a machine shop without involving additional sensing hardware, thus they were selected in this study as machining quality characteristics in order to evaluate cutting-fluid effectiveness. The questions that this study addressed are:

- How will the surface roughness of the turned parts be impacted by the soybean-based cutting fluid compared with the petroleum-based cutting fluid?

- How will the wear of the cutting tool be impacted by the soybean-based cutting fluid compared with the petroleum-based cutting fluid?

The procedures used in the evaluation of the soybean-based cutting fluid are given in Figure 1.

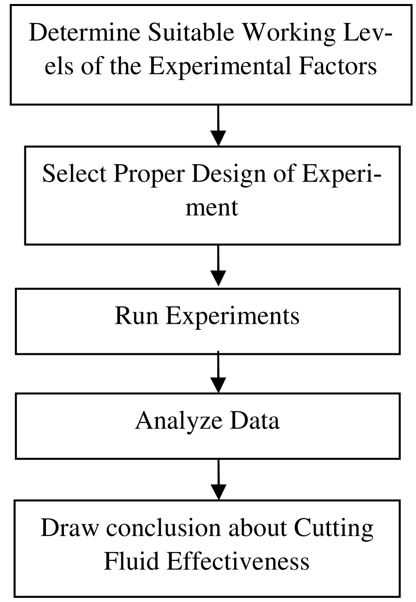


Figure 1. Study Procedures used in the Evaluation of the Soybean-Based Cutting Fluid

Experimental Study

Selection of Experimental Factors

Experimental factors were selected based on the literature review about machining theory and machining practice. Out of the three parameters—cutting speed, feed rate, and depth of cut—feed rate was found to play an important role in determining surface roughness and cutting speed was a significant factor impacting cutting-tool life [19]. In practice, all three machining parameters need to be applied at the same time and each can vary across a wide range of values. As with many other experimental studies on machining operations [14], [20-22], these three parameters were considered as independent variables in this study. Another control factor is cutting fluid condition: soybean-based, petroleum-based, and dry.

The cutting speeds and feed rates were selected with reference to the Machinery’s Handbook (27^{th} edition) and the catalog of the carbide insert for turning high carbon alloy steel. The levels of depth of cut were selected to emulate machine shop practice in consideration of both machining productivity and safety. The selected parameters along with their applicable codes and values are listed in Table 1.

Table 1. Parameters, Codes, and Level Values used for the Taguchi Design

Parameter	Code	Level 1	Level 2	Level 3
Control Factors				
Cutting Speed, ft/min (m/min)	A	300 (91.44)	340(103.632)	380 (115.824)
Feed Rate, ipr (mmpr)	B	0.008 (0.2032)	0.012 (0.3048)	0.016 (0.4064)
Depth of Cut, in (mm)	C	0.04 (1.016)	0.05 (1.27)	0.06 (1.524)
Cutting-fluid condition	X	dry cutting	soy fluid	petroleum fluid
Response Variable				
Surface Roughness Ra, µm				
Tool wear W*, mm				

* Tool flank wear will be measured after the cutting has completed a 7-inch long pass of the workpiece.

Design of Experiments

If a full factorial design were applied, at least 27 experimental runs must be conducted for each of the cutting-fluid conditions, even with single replication. For the three cutting-fluid conditions, the experimental study would be not only very time consuming but also costly because at least 81 tool inserts would be tested. Therefore, a Taguchi $L_9(3^4)$ orthogonal array shown in Table 2 was employed in the study which required 27 runs to cover the three machining parameters and the three cutting-fluid conditions. This table was used for recording the test results of surface roughness and tool wear data.

Experimental Materials and Supplies

- The workpiece material used in this study was E52100, a high-carbon, chromium-alloy steel. The chemical composition and major properties for workpiece material are listed in Appendix I. Because E52100 has great hardness and high wear resistance, the application of cutting fluids is a must when E52100 components are produced from machining processes due to its poor machinability (refer to Appendix I). The steel material was purchased as billets with a 7-inch diameter and was pre-cut into 9-inch lengths.

Table 2. Modified L_9 (3^4) Orthogonal Array Including Experimental Factors

L9 - orthogonal array					Cutting-fluid condition		
Run	**A (Cutting speed)**	**B (Feed rate)**	**C (Depth of cut)**	**D (Empty)**	**X1 (Dry)**	**X2 (Soy)**	**X3 (Petroleum)**
1	1	1	1				
2	1	2	2				
3	1	3	3				
4	2	1	2				
5	2	2	3				
6	2	3	1				
7	3	1	3				
8	3	2	1				
9	3	3	2				

- The cutting tool used was a carbide insert CNMG432 EGE AC700G (Sumitomo Electric Carbide, Inc.), which is coated with multi-phase Al_2O_3. The coating, along with a tough carbide substrate, makes it suitable for rough turning carbon steels and alloy steels.
- The soybean-based cutting fluid that was used—SoyEasy™ Cool-GHP Plus—is an environmentally friendly product produced by Environmental Lubricants Manufacturing, Inc. [18]. This cutting fluid was maintained at 5% concentration (by volume) through the entire experiment.
- The petroleum-based cutting fluid used was Castrol Clearedge 6510, produced by Castrol Industrial Americas. It is a semi-synthetic cutting and grinding fluid for ferrous metals. This cutting fluid was maintained at 5% concentration (by volume) through the entire experiment.

Experimental Hardware and Software Set-up

This experiment was conducted using the following hardware and software:

- CNC Turning Center: Haas SL-20 (Haas Automation, Inc).
- Surface Roughness Digital Measurement Device: Surtronic 25 Roughness Checker (Taylor Hobson, Inc). The setup for surface roughness measurement is shown in Figure 2.

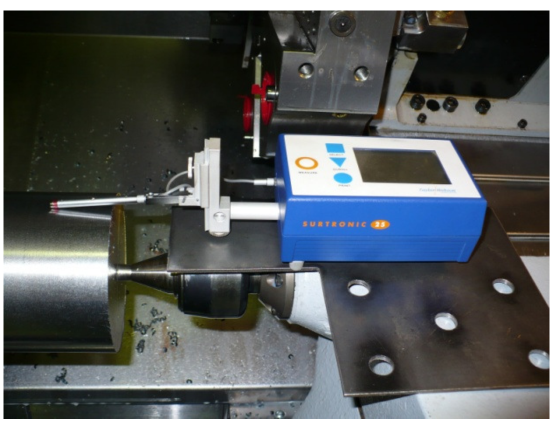


Figure 2. Setup of Surtronic 25 Roughness Checker

- Mitutoyo Toolmaker's Microscope with a magnification of 15 was used for measuring flank wear that occurred on the flank face of an insert resulting from abrasive wear of the cutting edge against the machined surface. The wear can be read as small as 0.001mm. The microscope and a picture of a worn insert taken under the microscope are shown in Figures 3 and 4.
- Microsoft Excel and JMP software packages for charting data and statistical analysis.

Figure 3. Microscope used for Tool Wear Measurement

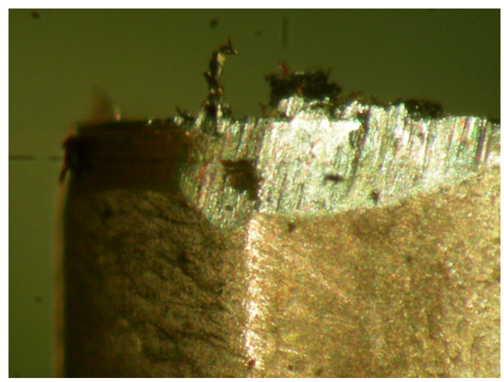


Figure 4. Flank Wear Example under Microscope

Data Collection

In the experiment, the workpiece material E52100 was prepared as 7" × 9" metal billets. It was chucked between the spindle chuck and the tailstock center in the Haas turning center, as shown in Figure 5. One specific tool insert was used to turn and clean off the billet surface to make sure that all tested inserts would cut the clean workpiece surface without any interference from rust or dirt. In Figure 6, a copper tube connected to the cutting-fluid orifice was directed to the insert and workpiece to flood the interface of the workpiece and the insert.

Each experimental combination was conducted only once across 27 experimental runs for all of the experimental combinations listed in Table 2. A complete randomization of the

27 cuts was not done since switching from one cutting fluid to another for each experimental run involved a thorough cleaning of the sump and flushing of all the fluid in the system. Therefore, the experimental runs were conducted in batches—turning at the soybean-fluid and petroleum–fluid, and dry conditions in sequence. The fluid tank and pipes were totally cleaned when the cutting fluids were switched. The sequence of the nine runs under each cutting-fluid condition was randomized in order to minimize other unforeseen factors that might bias the experimental results.

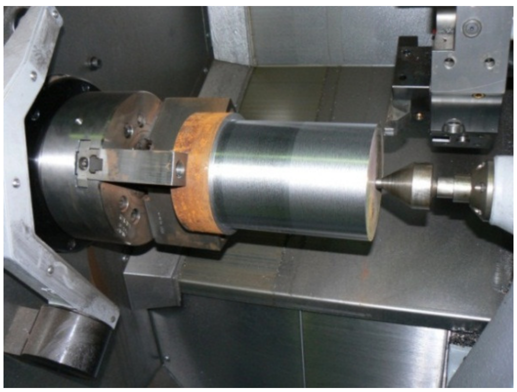


Figure 5. Workpiece after One Turning Path

An NC part program was written with different cutting parameters specified to let the Haas CNC turning center cut the work piece 7” long starting from the right end face. After the cutting pass, the surface roughness was measured at four spots evenly around the periphery of the billet. One picture of the measurements is shown in Figure 2. The average of the four measurements was recorded into Table 3.

After each cutting pass, the tool insert was removed from the tool holder and the flank wear was measured under the microscope. After the tool wear was measured, the tool was documented and stored, and a new tool insert was mounted into the tool holder for the next experimental run. The results of the surface roughness and insert flank wear measurements are shown in Table 3.

Figure 6. Cutting Fluid Applied to Insert and Workpiece

Data Analysis

Data Analysis on Surface Roughness

A visual examination of the data in Table 3 found that surface roughness, Ra, values for the soybean-based fluid condition (column X2) were consistently lower than for the dry condition (column X1) except that during run #2, the surface roughness was slightly larger (3.98 vs. 3.54). A sim-

Table 3. Surface Roughness and Tool Wear Data Collected in Experiment Runs

L9 - Inner Control Factor Array					Surface Roughness, Ra (mm)			Tool Wear, W (mm)		
Run	**A (speed)**	**B (feed)**	**C (depth)**	**D**	**X1 (Dry)**	**X2 (Soy)**	**X3 (Petro.)**	**X1 (Dry)**	**X2 (Soy)**	**X3 (Petro.)**
2	1	2	2		3.54	**3.98**	**6.32**	0.126	0.072	**0.157**
3	1	3	3		4.54	3.92	1.92	0.203	0.055	0.107
4	2	1	2		6.66	1.62	1.84	0.156	0.088	0.154
5	2	2	3		3.32	1.46	1.72	0.162	0.099	0.105
6	2	3	1		5.02	1.64	**5.78**	0.267	0.107	0.113
7	3	1	3		7.42	1.44	1.80	0.202	0.110	0.087
8	3	2	1		9.00	1.86	1.90	0.173	0.093	0.166
9	3	3	2		4.42	2.26	1.72	0.188	0.138	0.143

ilar result can be seen when comparing columns X3 and X1, which is the roughness comparison between the petroleum fluid and the dry conditions. However, for run #2, the Ra value for the petroleum condition was almost twice that for the dry condition (6.32 vs. 3.54); and, for run #6, the Ra value for the petroleum condition was slightly larger than the dry condition (5.78 vs. 5.02). Both of the comparisons indicated abnormal results because the surface roughness would normally be better when cutting fluids are applied. The abnormal data were not discarded and were treated as variations for analysis.

ANOVA Analyses on Surface Roughness

Analysis of variance (ANOVA) is an analytical approach in which the mean of a variable as affected by different factors or factor treatment combinations is analyzed. A one-way analysis of variance is the simplest form which can test differences between more than two groups or treatments by an F-test. According to the research questions, the hypothesis about surface roughness was:

H_0: There are no significant differences among the cutting-fluid conditions ($Ra_1=Ra_2=Ra_3$).

H_1: Not all of the averages for the three cutting-fluid conditions are equal. In other words, at least for one pair of treatments, surface roughness is different.

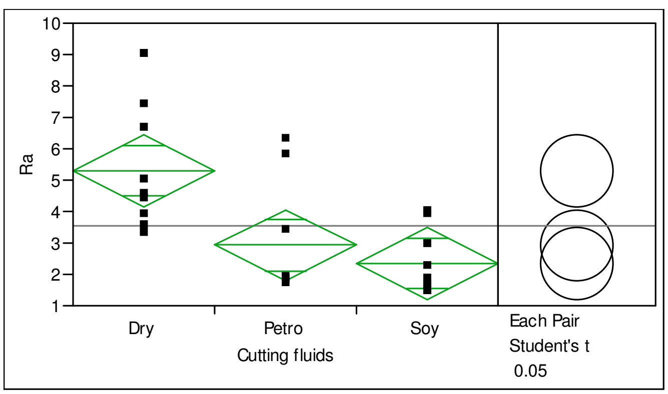


Figure. 7 One-way Analyses of Surface Roughness by Cutting Fluids

The statistical one-way analysis was conducted and the graphical display of the comparison results are shown in Figure 7. The longest horizontal line represents the mean and the other two short horizontal lines represent the 25th and 75th percentile values, respectively. The variation of surface roughness was large when no cutting fluids were applied; instead, for the soybean-based fluid condition, the surface roughness showed the smallest range of variation and the smallest average; for the petroleum-based fluid condition, a couple of surface roughness values fell far from the rest of the data, and the average value was in-between that of the dry and soybean conditions. The circles in the right column represent the probability of the response variable at three cutting-fluid conditions. A large portion of overlap of the two circles in Figure 7 indicated that the difference between the two cutting-fluid conditions may not be significant. The circle on the top (dry condition) does not have any overlap with the other two circles, indicating the surface roughness for the dry condition was different from the two cutting-fluid conditions. The result that there are significant differences among the three cutting-fluid conditions can be confirmed statistically from Table 4, because the small probability value (0.0021) given in the ANOVA analysis tells us that the variation in the observations was not caused by random variation alone. Therefore, the null hypothesis should be rejected.

Table 4. Analysis of Variance for Surface Roughness by Cutting Fluids

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Fluids	2	44.3344	22.1672	8.0379	0.0021
Error	24	66.1882	2.7578		
Total	26	110.5227			

T-test on Surface Roughness for Pairs Treatment

The hypothesis test above only tells us that there were significant differences among treatments in the experiment as a whole. Following the hypothesis test, the t-test was performed in order to identify which cutting fluid conditions generated the surface roughness differences. The least significant difference (LSD) can be computed by Equation (1)

$$LSD = t_{\alpha/2}\sqrt{MSE(\frac{1}{n_1}+\frac{1}{n_2})} \qquad (1)$$

where n_1 and n_2 are the number of samples collected for each cutting-fluid condition: $n_1 = n_2 = 9$. MSE is the mean square error displayed in Table 4: MSE = 2.7578.

If using student's t, $t_{a/2}$ is the t-value corresponding to the significant level a (pre-determined as 0.05) with 16 degrees of freedom: $t_{a/2} = 2.120$. Using the Bonferroni adjustment, a was set to 0.05 for the entire experimental treatment comparisons. As there were three pair-wise comparisons in this experiment (namely as dry vs. petroleum, dry vs. soy, petroleum vs. soy), the significant level for the pair-wise comparisons can be adjusted to 0.0167 (=0.05/3). Therefore, $t_{a/2}$ was the t-value at a probability of 0.0167 with 16 degrees of freedom: $t_{a/2}$ = 2.672. The LSD can be computed as follows.

$$LSD = 2.672\sqrt{2.7578 \times (\frac{1}{9} + \frac{1}{9})} = 2.091$$

Based on the calculated LSD, and because the differences in surface roughness means at the dry and petroleum conditions was 2.38 which was larger than the calculated LSD, the surface roughness results for the dry and petroleum cutting conditions were significantly different. Similarly, the surface roughness results for the dry and soy cutting conditions were significantly different, as their mean difference of 2.962 was larger than the LSD. It can be clearly seen that there was no difference between the petroleum and the soy cutting conditions. The above pair-wise comparison results are labeled in Table 5—the average of surface roughness for the dry condition is marked as level 1 (L1) and the other two as level 2 (L2). Tables 4 and 5 together tell us that the two cutting fluids did not produce significant differences in smoothing surface roughness, but the surface finish at the two wet conditions was statistically better than for the dry condition.

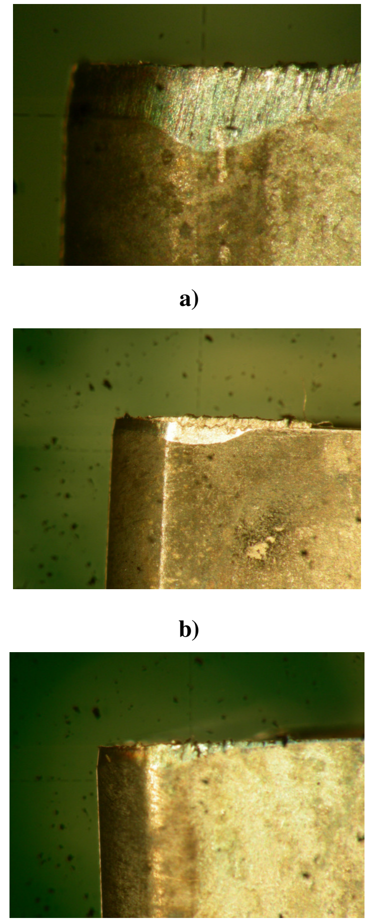
Table 5. Comparisons of Surface Roughness for each Pair using Student's t Test

Level	Label*		Mean
X1(Dry)	L1		5.311
X3(Petroleum)		L2	2.931
X2(Soy)		L2	2.349

* Levels (L1 and L2) not Connected by the Same Letter are Significantly Different.

Data Analysis on Tool Wear

Visual inspection of tool wear data at the three cutting-fluid conditions listed in Table 3 found that the tool wear for the two cutting-fluid conditions was consistently smaller than for the dry condition. There was only one abnormal result in run #2 in that the tool wear of the petroleum-based fluid condition was slightly larger than the value for the corresponding dry condition (0.157 vs. 0.126). This abnormal tool wear matched with the unusual surface roughness result that occurred in run #2. To some extent, this large tool wear may provide a partial explanation why such a high surface roughness occurred in run #2, since tool condition was an important factor impacting surface finish. Overall, all of the tool wear data in Table 3 are smaller than the flank tool wear of 0.5mm, which is the cutoff value set by ISO for defining an effective tool life. Figure 8 shows sample pictures of the tool inserts with the flank wear for dry, soybean, and petroleum conditions.



a)

b)

c)

Figure 8. Tool Inserts Along with Flank Wear at Different Cutting-Fluid Conditions— a) Dry Condition, b) Soy Fluid, c) Petroleum Fluid (all seen at magnification 15)

ANOVA Analyses on Tool Wear

The one-way ANOVA analysis was conducted regarding the tool wear for the three cutting conditions. According to the research questions, the hypothesis for tool wear was:

H_0: There are no significant differences among the cutting fluid conditions (W_1=W_2=W_3).

H_1: Not all of the tool wear averages for the three cutting -fluid conditions are equal.

The ANOVA results are shown in Table 6; the graphic results are displayed in Figure 9. The average tool wear for the soybean cutting fluid condition (column 2 in Figure 7) was at the lowest level, the average tool wear for the dry cutting was at the highest level, and the one for the petroleum cutting fluid was in-between. Representing the probability, the circle for the dry condition stands far away from the other two circles, which means that the tool wear for the dry condition was significantly different from the other two conditions. In other words, the application of cutting fluids significantly reduced tool wear. The small probability value (<0.0001) given by the F-test in the ANOVA analysis in Table 6 confirmed this observation. Therefore, the null hypothesis should be rejected.

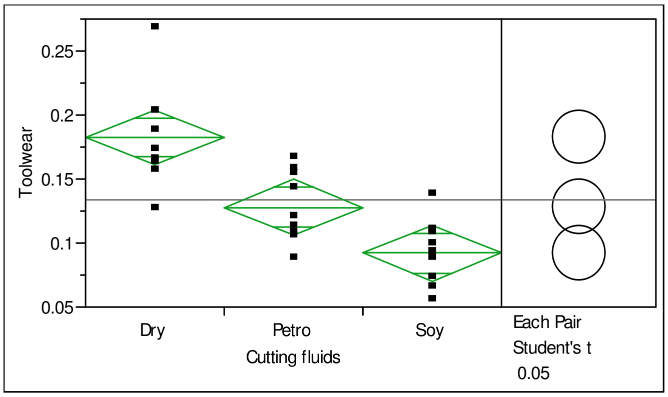


Figure 9. One-way Analyses of Tool Wear by Cutting Fluids

Table 6. Analysis of Variance for Tool Wear by Cutting Fluids

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Fluids	2	0.0374055	0.018703	18.6739	<.0001
Error	24	0.0240371	0.001002		
Total	26	0.0614426			

T-test on Surface Roughness for Pairs Treatment

The ANOVA analyses in Table 6 indicated that there were significant differences among the three cutting-fluid conditions. By calculating the LSD tool wear, performing the t-test was able to identify which cutting-fluid conditions made a significant difference in reducing tool wear. Using Equation (1), the Bonferroni-adjusted LSD for tool wear was calculated as

$$LSD = 2.672\sqrt{0.001002 \times (\frac{1}{9} + \frac{1}{9})} = 0.0398$$

From Table 7, the tool wear differences of the pair-wise comparisons—dry vs. petroleum, and dry vs. soy—were 0.054 (=0.182-0.128) and 0.092 (=0.182-0.092). Because these two differences were larger than the LSD tool wear, it can be concluded that applying the two cutting fluids significantly reduced tool wear. As noticed, there was a very small portion of overlap between the two circles representing the petroleum and the soy cutting-fluid conditions (see Figure 9). The tool wear difference for the petroleum and soy conditions was 0.036, which was slightly smaller than the Bonferroni-adjusted LSD of 0.0398, but larger than the calculated LSD from the student's t-value (2.120). The LSD from Student's t was computed as

$$LSD = 2.120\sqrt{0.001002 \times (\frac{1}{9} + \frac{1}{9})} = 0.032$$

From the student's t-test, the tool wear results were significantly different for the petroleum and soy cutting-fluid conditions. Therefore, the three cutting-fluid conditions are labeled as L1, L2, and L3, respectively, in Table 7. The pair -wise comparison results concluded that the three tool wear averages were significantly different by pairs, and the soybean fluid performed statistically better than the petroleum alternate in reducing tool wear.

Table 7. Comparisons of Tool Wear for each Pair using Student's t Test

Level	Label*			Mean
X1(Dry)	L1			0.182
X3(Petroleum)		L2		0.128
X2(Soy)			L3	0.092

* Levels (L1, L2, and L3) not Connected by the Same Letter are Significantly Different.

Conclusions and Summary

An L_9 (3^4) Taguchi design was used to compare an experimental soybean-based cutting fluid against dry and petroleum-based cutting fluids in turning operations. The experimental data analysis revealed that the soybean-based cutting fluid performed better than the petroleum alternate product in terms of controlling tool wear, and both of the two cutting fluids performed similarly well in reducing surface roughness. The experimental study covered three machining parameters and three cutting-fluid treatments. If a full factorial DOE approach were to be used, at least 81 (3×3×3×3) data points would need to be collected in order to include all of the factors. The selected L_9 (3^4) orthogonal array with a total of 27 experimental runs saved a lot of resources. Providing supporting evidence for the manufacturing professionals who may consider green manufacturing and substituting the conventional cutting fluids with the bio-based alternates, the experimental approach presented here can be a reference applicable to real manufacturing planning practice.

It cannot be denied that the Taguchi Design is a fractional factorial design in nature. Considering the limited amount of resources, this study focused on the primary comparison of the machining performance difference brought by different cutting-fluid conditions. As noticed, there were no repetitions for the experimental run under each cutting-fluid condition. If more data were collected in this undergraduate research project, the signal/noise ratio could be introduced to identify the optimal cutting parameters for each of the cutting fluids.

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Appendix I. Chemical Composition and Major Property Data for Workpiece Material E52100

Mechanical Property	
Hardness, Brinell	229
Modulus of Elasticity	210 GPa
Tensile Strength	0.74 GP
Machinability	40% (Based on 100% machinability for AISI 1212 steel)
Composition of Chemical Components	
Carbon, C	0.980 - 1.10 %
Chromium, Cr	1.45%
Iron, Fe	97.0 %
Manganese, Mn	0.35 %
Phosphorous, P	<= 0.025 %
Silicon, Si	0.230 %
Sulfur, S	<= 0.025 %