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ABSTRACT

Metalworking fluids (MWFs) play a significant role in machining operations. Despite their importance, the manufacturing industry lacks tools to make functionally sound and economical decisions about them.

In this research project, a second generation drilling testbed was developed to evaluate the performance of MWFs with respect to lubricity and cooling capacity. A desktop drilling machine was used to make the testbed with a load cell sensor and a thermocouple located in the oil-hole of the drill. The testbed characterized MWFs based on torque, thrust, and temperature measurements. A standardized test procedure was developed to ensure that comparisons of fluids were accurate, repeatable, and representative of the actual differences in the fluids. System repeatability was found to be very good with a coefficient of variation well under 0.1. The system was found to determine differences within 1-2.9% for torque, 1.4-2.5% for thrust, and 2.7-8.2% for temperature based on five replicates per experimental condition and an $\alpha = 0.05$ statistical analysis.

Ten MWFs were chosen, representing a cross-section of soluble oils, semi-synthetics, and synthetic products from a variety of manufacturers. The performance of these fluids at a 10% concentration was analyzed based on a set of four separate comparative experiments designed to compare various drilling conditions and reveal how the MWFs performed based on changes of workpiece material, feedrate, and dilutent. The results were evaluated within each experiment by comparing how individual fluids performed within their type and how fluid types performed with respect to each other. Comparative analysis was also conducted among separate experiments to determine how changes in feedrate, workpiece material, and dilutent affect MWF performance. Conclusions based on the data analysis are presented.

Additional MWF evaluation tests were used to further characterize the fluids. Tests for viscosity, surface tension, emulsion stability, and corrosion inhibition were conducted. These results were compared with the lubricity and cooling results to check for correlation. General trends indicated a correlation between fluid performance in lubrication and viscosity and surface tension results. Surface tension was found to be more a function of the emulsifiers and additives used in a fluid than the concentration of oil, while viscosity showed a definite correlation with oil content. It was also found that the synthetic fluids showed the most resistance to fluid breakdown due to hard water as measured by emulsion stability titration testing. There was no correlation found between type of fluid (soluble oil, semi-synthetic, and synthetic) and corrosion inhibition or surface tension.

1. INTRODUCTION

Metalworking fluids (MWFs) are critical for machining engineering materials efficiently and effectively. These fluids perform multiple functions including lubrication, cooling, corrosion prevention, and chip evacuation [1]. The high speed machining and close tolerances required in the current manufacturing environment are made possible partly by using MWFs [1]. Choosing the correct MWF is very important for machining operations because of the significant impact it can have on tool wear. However, this choice is difficult because decision-makers have little unbiased, independent, and quantitative information on MWF product attributes using multiple criteria. An independent testing procedure and corresponding database is needed to help end-users determine the correct fluid for a given operation.

Most publications that deal with MWF selection do so in a broad way by describing the three categories of soluble oil, semi-synthetics, and synthetics and referring to the pros and cons of each category [1, 4-6]. The guidance given by these publications is limited to advice about which chemical additives to look for in order to capture certain MWF properties, e.g., alkanolamides as emulsifiers to reject tramp oil, fatty acids to regulate clarity and viscosity, or ethanolamines for corrosion inhibition [1]. In the late 1990s, the MTAMRI (Machine Tool Agile Manufacturing Institute) partnership at Michigan Technological University developed a cutting fluid evaluation software testbed (CFEST) [7] that provided a tool to analyze the environmental impact of cutting fluid in the machining process. Tan et al. [8] have developed a decision-making framework model for cutting fluid selection based on green manufacturing processes using a fuzzy matrix approach. The National Center for Manufacturing Sciences published a MWF optimization guide in 1997 that compares and contrasts over 150 MWF functionality tests [6]. In 2000, a drilling testbed approach to MWF performance was developed by Upton [9] that allowed measurement of cutting forces. Later, Greeley et al. [10] took this approach a step further by developing a similar drilling testbed that added the ability to measure tool temperature using a thermocouple embedded in the drill as well as measuring cutting forces using a dynamometer to measure torque and thrust.

There are several tests for lubricity and cooling based on tapping, turning, and drilling methods [11]. The drilling testbed built by Greeley et al. [10] was able to test for cooling performance using tool temperature at the cutting interface and was also able to accurately evaluate cutting forces. However, the method had several issues that need to be resolved to allow more accurate and comprehensive evaluation for MWF performance. These issues are:

- Large cost and laboratory footprint of the milling/drilling/tapping machine used;
- Fluid application not indicative of industry conditions; and
- Lack of standardized testing procedure.

In addition to these issues, the testing procedure was too narrow in the fluid characteristics measured. In order for the MWFs to be adequately characterized, the testing procedure must be expanded to look at parameters beyond lubricity and cooling, such as viscosity and emulsion stability.

While there are broad recommendations about how MWF types differ, there is no database that is able to compare MWF performance across all three MWF types as well as fluids of the same type from competing manufacturers. Fluid manufacturers often provide their own fluid performance results from their own testbeds. However, many of the tests used are not reliable or repeatable and the tests used by different manufacturers are not always the same [3]. It is important that end-users are able to have an independent and unbiased comparison of comparable fluids from different manufacturers in order to help them make educated decisions. A database of fluid performance that contains data for soluble oil, semi-synthetic, and synthetic fluids from a variety of fluid manufacturers would be invaluable to end-users during their selection process.

There were three objectives for this project:

1. To create a second generation MWF characterization drilling testbed and standardized testing procedure;
2. To use the testbed to evaluate ten MWFs in terms of cooling and lubricity; and
3. To expand the characterization of the ten MWFs to other areas such as performance in emulsion stability and corrosion inhibition.

The first research objective, creating a second generation testbed, is covered in Section 2 of this report, which talks about the components, standardized procedure, and statistical analysis. The second research objective, evaluating ten MWFs in terms of lubricity and cooling, is covered in Section 3, which contains drilling experiment results and analysis evaluating the performance of MWFs with respect to torque, thrust, and temperature values for varying cutting parameters. The third research objective, expanding the database of MWFs by conducting additional tests, is covered in Section 4, which provides results of viscosity, surface tension, emulsion stability, and corrosion inhibition tests. The fifth, and final, section draws conclusions from the assembled data and provides a summary table of MWF performance for the ten fluids.

2. DEVELOPMENT OF A SECOND GENERATION DRILLING TESTBED AND PROCEDURE

2.1 Development of Second Generation Drilling Testbed

The first research objective of the project was to create a second generation MWF characterization drilling testbed and a standard testing procedure to be used with it to ensure accurate and repeatable data collection. This testbed was based on the first generation testbed developed by Greeley et al. [10], which was constructed with the objective of determining the effect of gradual component depletions on MWF performance. The Greeley et al. testbed was experimentally verified to be more sensitive to small changes in MWF composition than two common MWF evaluation techniques, the tapping torque test and the coefficient of friction test [10]. However, the first generation testbed had several issues that needed to be improved upon for a more accurate and comprehensive evaluation for MWF performance and to allow it to be more universally available to prospective testers.

The Greeley et al. [10] drilling testbed employed a Mori-Seki TV-30 Light Milling/ Drilling/ Tapping Machine. It measured torque and thrust using a Kistler dynamometer (type 9272). Thrust derives a larger component of its force response from the action of the chisel edge, which is an indentation/deformation process. The torque component involves the moment arm action on the cutting edge, which has a shearing chip formation mechanism.

The Greeley et al. [10] testbed applied MWF by filling a counterbore in the workpiece with MWF prior to commencing drilling. This application procedure is not particularly indicative of industrial use of MWFs. Further, the primary goal of Greeley et al. [10] was to establish a testing method and procedure and demonstrate its efficacy. Therefore, the large footprint and high cost ($75,000) of the industrial-sized milling/drilling/tapping machine made it impractical for use outside of a large testing facility. The Kistler dynamometer used to gather force data is also a very expensive ($25,000-30,000) instrument and was more sophisticated than necessary for the very specific force measurements needed in the drilling testbed.

The objective of this work was to develop a reliable and affordable testbed with an eye toward commercialization and to develop a standardized testing procedure. It is important that the results gathered using the testbed be both accurate and repeatable to ensure reliable testing of MWF performance and true differences. A dedicated testbed used only for the single act of MWF characterization through drilling will enhance the commercialization of the system by offering s smaller physical and economic footprint. The improvements made to the first generation testbed in the development of the second generation testbed are described in the next several subsections.

2.1.1 Desktop Machine

When developing the second generation drilling testbed, it was important that the finished product be small and inexpensive enough that manufacturing facilities wanting to carry out their own fluid comparisons would be able to build or purchase one of their own. To this end, a smaller desktop machine, a 1.5kW MSC Milling & Drilling Machine[1] ($2,149), was used (Fig. 1). This machine can be used solely for evaluating MWFs, while having a much smaller footprint than the previously used Mori-Seki TV-30. The available feedrates for the MSC machine are 0.234, 0.1778 and 0.1016 mm/rev, and the available rotational speeds range from 125 rpm – 2500 rpm. These conditions are consistent with those used in an industrial setting for the drill material geometry and the workpiece material. The purpose of using the desktop test facility was to determine if such a set-up could be used for the analysis of MWF effectiveness. The testbed employed is, in fact, an industrial grade drilling machine and could be used by both MWF manufacturers and those wishing to apply MWF to a given application to determine the most effective MWF.

2.1.2 Workpiece and Fixture

The workpiece used in the testbed was cylindrical, measuring 25.4mm in diameter with a length of 50.8mm. The control workpiece material chosen was AISI 1018 due to its frequent usage as a manufacturing material. An alloy steel (4340) was also used in certain experiments.

Figure 1. MSC Milling & Drilling Machine

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[1] www1.mscdirect.com

The AISI 1018 showed excellent results for the MWF performance experiments conducted by Greeley et al. [10] and Bittorf et al. [18]. The information on the AISI 1018 and 4340 alloy steel is given in Table 3 and 4 (Chapter 3). The workpiece was held during testing using a custom fixture that bolts to the upper mounting flange of the load sensor. The design of the fixture can be seen in Fig. 2 where the dimensions are in millimeters. The actual fixture used in the testing is shown in Fig. 3.

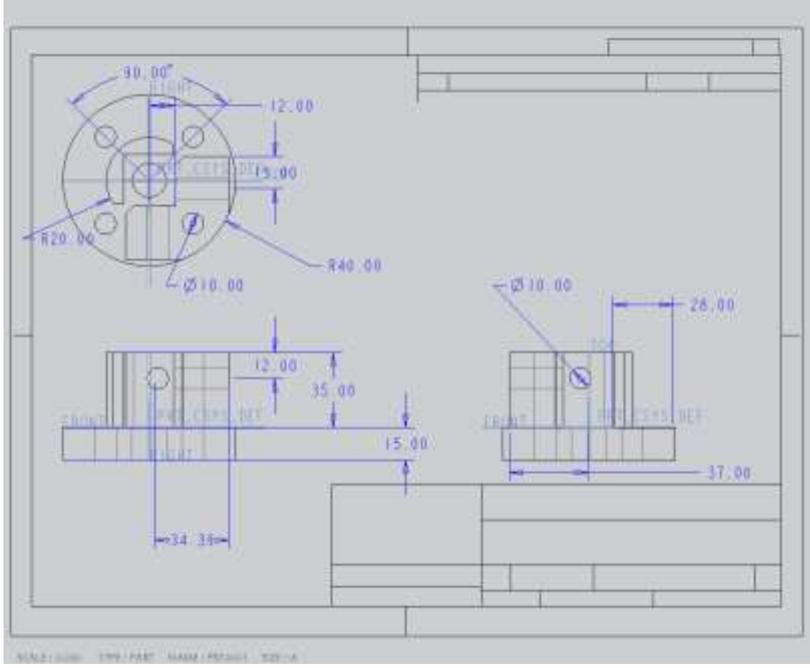

Figure 2. Fixture Design

Figure 3. Workpiece Fixture

2.1.3 Drills used in the Testbed

The drill selected for use in the testing was a 12.7mm diameter high-speed steel oil-hole taper length black oxide drill with 118° point angle, 33° helix, a notched point and a 1.07mm chisel edge. The 12.7mm diameter was chosen so that the oil-hole would be large enough to allow the thermocouple to be threaded through it. According to Byers [1], the use of uncoated high speed steel (HSS) drills has been found to be an effective tool for discriminating between different cutting fluids. While it is common to apply various coatings (titanium nitride, zirconium nitride, etc.) to HSS drills to extend drill life, in this study only uncoated HSS drills were used.

2.1.4 Data Acquisition System

The data acquisition system for the second generation testbed used a National Instruments SCC-68[2] I/O connector block (Fig. 4) and an E Series DAQ device to receive the analog signal from the load sensor and thermocouple. The sampling rate was set at 2000 samples per second. Labview™ data acquisition software was used to record the data and provide it to a Matlab™ interface.

Figure 4. NI SCC-68 I/O Connector Block

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[2] www.ni.com

2.1.5 MWF Application

The first generation testbed applied MWFs by causing a drill to pass through a pool of approximately 5 ml of fluid located in a counterbore in the workpiece. The disadvantage of this application method is that such a small volume of fluid can easily heat up faster than if fluid were continually applied via the flood method. Application in the machining industry is typically accomplished by flooding the workpiece/tool interface with MWFs pumped through nozzles. Active flooding of MWF also produces a significant "flushing" effect that is necessary for chip evacuation and temperature control, which was lacking in previous design. In the second generation testbed, flood application was used to create a more industry-realistic condition. A 0.1 hp coolant and recirculating pump system, manufactured by Enco[3], with a maximum flow rate of 35 L/min was used to accomplish MWF application.

Since multiple MWFs were studied in this research and it was important that they not be contaminated through mixing, the MWF application system needed to be easily cleaned or replaced after every drilling experiment. Thus, individual containers were used for each MWF with the pump system being moved among them. The pumping system was flushed with water before introducing a new fluid in order to prevent carryover. Figure 5 shows the pump for flooding MWF and a MWF container. The nozzle used to apply the flood coolant can be seen in the upper right of Fig. 5.

Figure 5. Pump and MWF Container

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[3] www.use-enco.com

2.1.6 MWF Splatter Shield

A stainless steel MWF splatter shield was designed to capture the used MWF after it has contacted the drill and workpiece. The MWF splatter shield was made out of stainless steel to eliminate corrosion opportunities. It was constructed so that it can be fixed between the workpiece fixture and the load sensor by the use of three set screws. This allowed the splatter shield to be inserted and removed readily so that it can be cleaned with minimal difficulty. To enable the MWF splatter shield to drain, a one inch diameter hole was made and a nozzle was welded in place. A tube was connected to the nozzle and MWF flowed from the shield to a fluid disposal tank from which it could be discarded. O-rings were used to create a seal between the shield and the fixture to avoid MWF leakage. Figure 6 shows the MWF splatter shield. The splatter shield captured the MWF during the flood application testing and diverted it the disposal tank. In addition to capturing excess fluids, the splatter shield also captured machined chips.

2.1.7 Thrust and Torque Measurement

The four component dynamometer used in the Greeley et al. testbed [10] was large, costly, and its range of force measurement is unnecessarily wide for the application. To make the second generation testbed more economical, a 2-component load cell sensor from Kistler Type 9345A[4] was selected for torque and thrust measurements.

Figure 6. MWF Splatter Shield

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[4] www.kistler.com

The load sensor was 42mm high and the total height of the load measurement block with two mounting flanges, as shown in Fig. 7, was 68mm high. Measuring ranges for thrust and torque were from -10kN to 10kN for thrust, and from -25Nm to 25Nm for torque, respectively. These ranges were more than adequate for drilling tests employed to evaluate MWF performance. The sensitivity of this load cell was -3.8pC/N for thrust and -220pC/Nm for torque. The sensor was calibrated at the factory prior to shipping. According to the manufacturer, the load cell sensor does not need to be routinely calibrated.

As shown in Fig. 7, the 2-component torque and thrust load cell sensor has two mounting flanges. The bottom mounting flange was then clamped to the drill base while the top was bolted to the workpiece fixture. Figure 8 shows where the load cell sensor was located relative to other system components. The MWF shield has been removed for Fig. 8 to allow the other components to be seen. During normal usage, the MWF shield was clamped between the top mounting flange of the load cell sensor and the workpiece fixture.

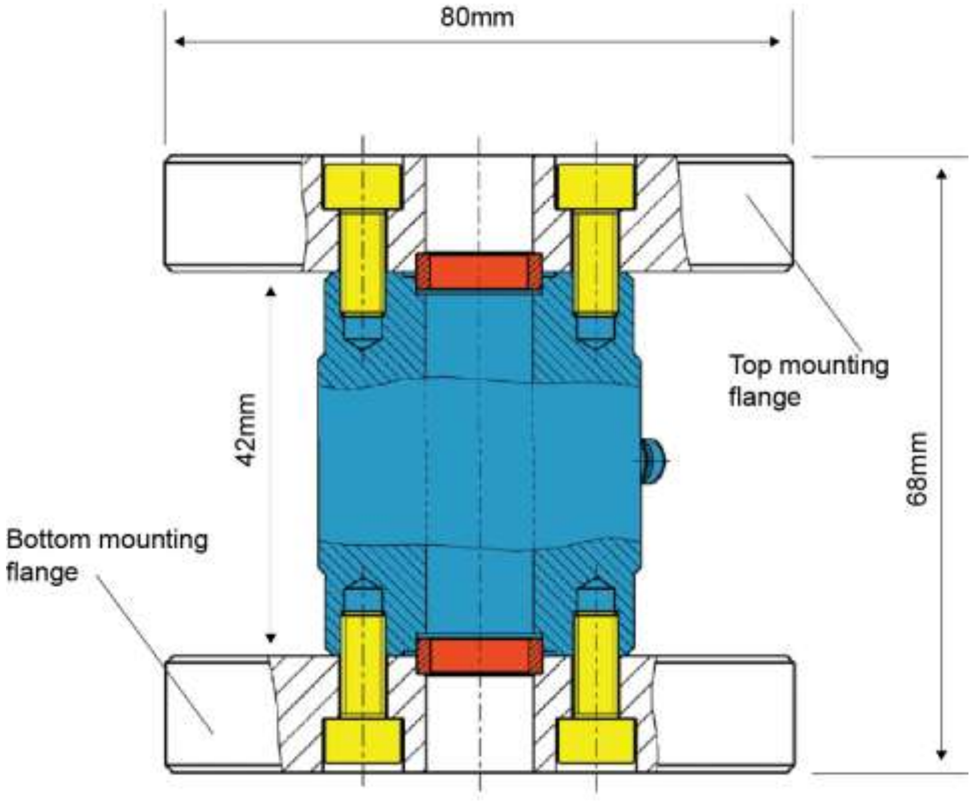

Figure 7. 2-Component Load Cell Sensor with Top and Bottom Mounting Flanges

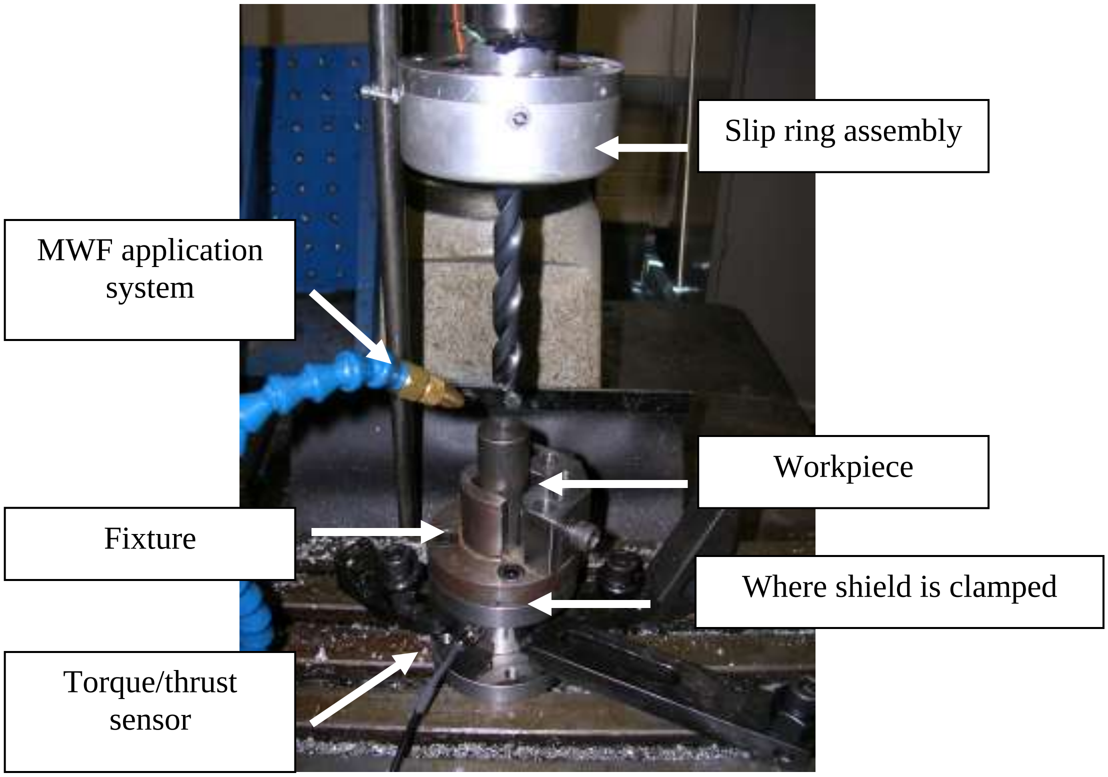

Figure 8. Testbed Configuration

2.1.8 Temperature Measurement

Temperature measurement was accomplished using an iron/constantan (T-type) thermocouple from Omega[5]. The range of the thermocouple was -250°C to 350°C with a maximum error of 1.0°C. The thermocouple passed through the oil-hole in the drill and it was affixed at the drill surface behind the cutting edge by epoxy. A slip ring, mechanism Fabricast Model 1984[6], was used for carrying the temperature signal from the rotating drill to the data acquisition hardware. The thermocouple was calibrated in an ice bath (0℃), at room temperature, and in boiling water (100℃) after it was affixed to a new drill. The calibrated slip ring acquired from the manufacturer was used for collecting the temperature data. The assembly of the thermocouple and slip ring with the drill is presented in Fig. 9. The components of the second generation drilling testbed are summarized in Table 1.

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[5] www.omega.com

[6] www.fabricast.com

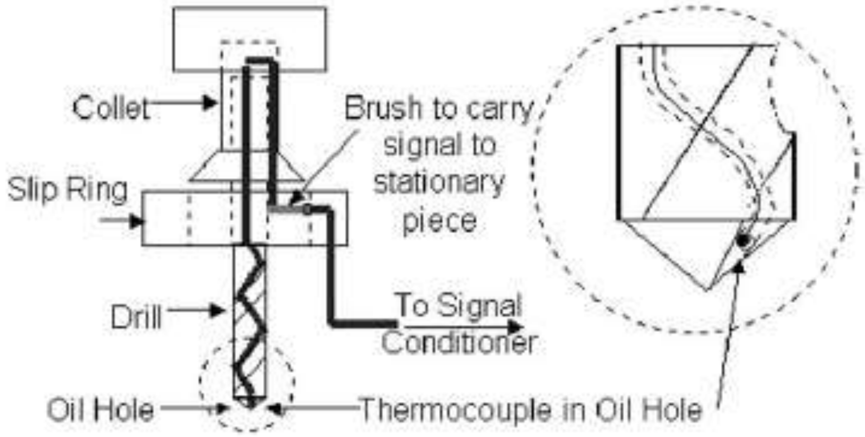

Figure 9. Thermocouple Wiring Diagram

Table 1. Equipment and Components Required for the Second Generation Testbed

Equipment and Components		Unit Price
Desktop machine	MSC Milling & Drilling Machine	$2,419
Drill, Workpiece and Fixture	12.7mm HSS Drill	$110
	Fixture	$500
	AISI 1018, AISI 4340	$5
Data Acquisition System	I/O Connector Block (NI SCC-68)	$300
	Labview^{TM}	$1,000
MWF Application system	Enco 0.1hp MWF pump	$200
MWF Splatter Shield	Stainless steel MWF splatter shield	$200
Thrust and Torque Measurement	2-component sensor for torque and thrust from Kistler (Type 9345A)	$7,100
	Dual mode charge amplifier	$1,500
	Cables and connectors	$500
Temperature Measurement	Slip ring assembly from Fabricast (Model 1984)	$1,000
	Signal conditioner from ANALOG DEVICES	$300
	Omega T-type thermocouple	$20
Total Price		$15,154

2.2 Standardization of MWF Performance Evaluation Procedure

The second major task in creating the second generation MWF performance evaluation drilling testbed was to standardize the testing procedure. Given that the goal was to develop a testbed that will be used by research and design technicians in laboratory and industry settings, it is important to provide a step-by-step procedure for setting-up and operating the apparatus, as well as data recording and statistical analysis. This standardized testing procedure is designed to ensure that comparisons of fluids are accurate, repeatable, and representative of the actual differences in the fluids.

The test procedure to be used with the testbed is as follows:

1. Prior to testing, create a break-in condition on all drills by drilling twenty (20) 12.7mm deep holes in AISI 1018 steel using a semi-synthetic MWF (Castrol Clearedge 6519 was used in this report). The number of twenty was determined by running several tests.
2. Prior to testing, rinse the drill and workpiece with acetone to remove machining oils and contaminants and allow them to dry.
3. Remove any residual water or fluid inside the hoses and nozzles of the MWF application system by having MWF flow through the nozzle for a few seconds prior to each drilling test.
4. Place the MWF application nozzle 10 cm from the workpiece with an angle of 40° from the face of the workpiece. If the nozzle is too close to the workpiece, the chips from the drilling process could interfere with the MWF application process.
5. Start MWF flood application at 20L/min using virgin MWF. 20L/min is about two-third of the maximum flow rate. If the flow rate is too high, it can cause the location of nozzle to change during operation due to the strong flow force.
6. Drill a 12.7mm deep hole in the workpiece. This value was selected based on Greeley et al.[10] in which it was determined that if the hole is too deep, MWF does not completely fill the hole during cutting, thus giving misleading data on MWF effectiveness.
7. Record cutting forces and temperature data continuously throughout the using data acquisition software.
8. Each individual test should be replicated 5 times to provide a sample size large enough for reasonable sensitivity in terms of the ability to detect differences when they are present.

The torque and thrust responses for each test are the average of the respective cutting force data recorded during the time that the drill was fully engaged in the workpiece, as shown in Fig. 10. Temperature responses are measured as the maximum observed temperature during the drilling cycle as shown in Fig. 11. It is common in a testing procedure of this type to drill no more than the equivalent of one diameter in depth at which point torque and thrust will increase. Further, as mentioned earlier, if deeper holes were to be used in the test, the ability of the MWF to reach to the bottom of the hole could be compromised. While, the temperature measurements are not stable at this depth, for comparative testing purposes, the test procedure would be valid. The fact that different MWFs additives may become operative at different temperatures is an issue beyond the scope of this testing procedure. The data shown in Figs. 10 and 11 was recorded during drilling of AISI 1018 steel with a feedrate of 0.1016 mm/rev, a cutting speed of 33.515 m/min, using a semi-synthetic MWF Castrol Clearedge 6510 at 10% concentration.

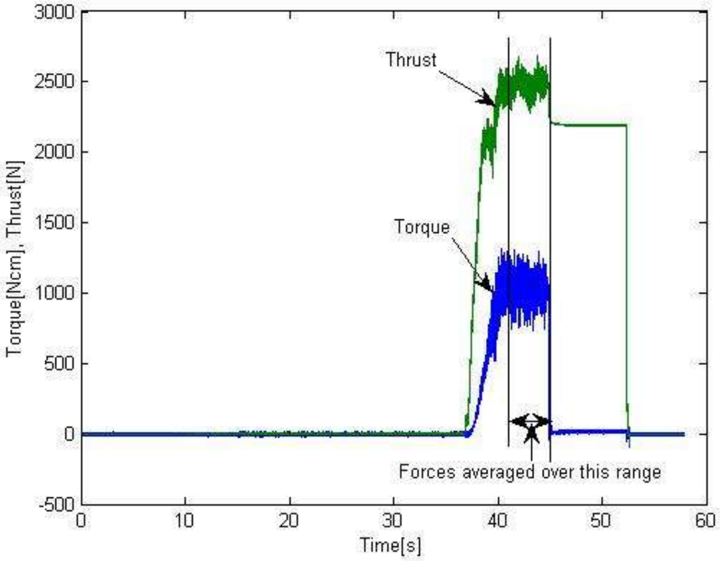

Figure 10. Force Data

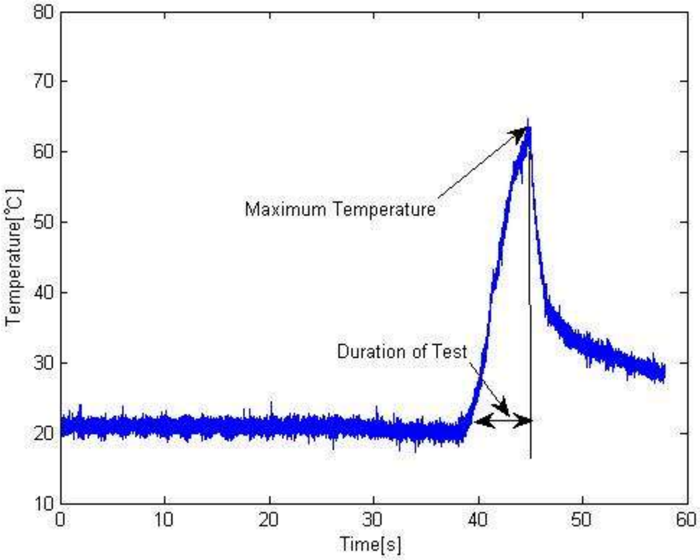

Figure 11. Temperature Data

2.3 Repeatability and Sensitivity of the Second Generation Testbed

2.3.1 Repeatability of the Second Generation Testbed

Table 2 provides an example of the torque, thrust and temperature values where each value in the "Average" column represents the arithmetic mean of the five replicates for a given MWF. Coefficient of variation (COV) is calculated by dividing a given standard deviation value by the corresponding average value.

Table 2. Example of Torque, Thrust and Temperature Values for Four Typical Semi-Synthetic MWFs

Type	Fluid	Average	Standard deviation	COV
Semi-synthetic	**6510**			
	Torque (N m)	10.45	0.22	0.021
	Thrust (N)	2554	42.24	0.017
	Temperature (°C)	67.86	3.59	0.053
	6519			
	Torque (N m)	10.49	0.20	0.019
	Thrust (N)	2573.8	48.78	0.019
	Temperature (°C)	66.98	3.31	0.049
	XXL			
	Torque (N m)	10.36	0.25	0.024
	Thrust (N)	2531	48.22	0.019
	Temperature (°C)	73.62	5.52	0.075
	SC230			
	Torque (N m)	10.24	0.16	0.015
	Thrust (N)	2510.8	23.11	0.010
	Temperature (°C)	77.06	4.67	0.061

The coefficient of variation is a good indicator of the repeatability of a system with a value below 0.1 generally indicating a repeatable system. According to Table 2, the maximum COV for the cutting force responses, torque and thrust, recorded by the load sensor was 0.021 and the maximum COV for temperature as recorded by the thermocouple was 0.075. These values are well under 0.1 and indicate a very repeatable system, especially in terms of cutting forces.

2.3.2 Homogeneity of Variance

It is often the case that testing conducted under similar conditions will have very similar variation levels. The assumption of homogeneity of variance allows the ensuing statistical analysis to employ a pooled variance estimate, with the associated smaller sampling error. In order to check for the appropriateness of this assumption, Bartlett's test [14] was used. This test computes a statistic whose sampling distribution is closely approximated by a chi-square distribution. The test statistic is given by

$$\chi^2_{calc} = \frac{M}{c}, \tag{1}$$

where

$$M = (N - m)\ln s_p^2 - \sum_{i=1}^{m}(n_i - 1)\ln s_i^2 \ , \tag{2}$$

$$c = 1 + \frac{1}{3(m-1)}\left[\left(\sum_{i=1}^{m}\frac{1}{n_i - 1}\right) - \frac{1}{N-m}\right], \tag{3}$$

$$s_p^2 = \frac{\sum_{i=1}^{m}(n_i - 1)s_i^2}{N-m}\ , \tag{4}$$

n_i is the sample size for each replicate set, m is the number of samples, N is the total number of responses, and s_i^2 is the independent variance of each sample set. We will reject the assumption of equality of the variances if $\chi^2_{calc} > \chi^2_{m-1,\alpha}$, where $\chi^2_{m-1,\alpha}$ places α in the upper tail of the chi-square distribution with $m-1$ degrees of freedom.

An example is provided using torque values presented in Table 2. The following statistics are calculated for a Bartlett's test with $\alpha = 0.01$:

$$\chi^2_{calc} = 0.7063$$

$$\chi^2_{m-1,\alpha} = 9.21$$

$$\chi^2_{calc} < \chi^2_{m-1,\alpha}$$

Therefore, the variance associated with each of the sets of four torque values in Table 2 can be assumed to be all equal. Based on this, the variance estimates for each trial can be pooled using Eq. (4), viz., $s_p^2 = 447.04$. The use of pooled variance greatly enhances the sensitivity of the test by increasing the degrees of freedom associated with the estimate of the error variance.

Once homogeneity of variance has been established the statistical difference between any pair of averages can be determined by t-test using the pooled variance estimate,

$$t_{calc} = \frac{\overline{X_1} - \overline{X_2}}{\sqrt{\frac{2s_p^2}{n}}} \tag{5}$$

Using 6510 and 6519 MWFs' torque values from Table 2, the t value from Eq. (5) is calculated as $t_{\text{calc}} = 0.2692$. The reference t statistic was $t_{16,0.975} = 2.120$, with 16 degrees of freedom for α=0.05. Since $t_{calc} < t_{16,0.975}$, the performances in terms of torque for 6510 and 6519 were not statistically different.

2.3.3 Sensitivity of Testbed

The sensitivity of the testbed was calculated as the maximum difference between means that would trigger a "not different" response on a *t*-test based on the assumption of homogeneity of variance and the use of a pooled variance. When a *t*-test with α=0.05 is used for testing with 5 replicates of each individual test, the testbed was found to be able to determine differences in torque with a sensitivity of 1-2.9%, thrust with a sensitivity of 1.4-2.5%, and temperature with a sensitivity of 2.7-8.2%, with the actual sensitivity depending on the testing conditions.

2.4 Summary

In this section, the creation of a second generation MWF characterization drilling testbed was discussed and the testing procedure was described.

1. The second generation testbed consisted of six main parts including a desktop drilling machine, drill, workpiece, and fixture; data acquisition system; MWF application system; MWF shield system; load cell for thrust and torque measurement; and a thermocouple for temperature measurement .
2. An eight-step testing procedure was developed and presented to ensure accurate measurements. Five replicates of each individual test are recommended for an adequate sample size for reasonable sensitivity in terms of differences.
3. Coefficient of variation results from initial testing showed a maximum coefficient of variance of 0.021 for the load cell measurements and 0.075 for the thermocouple measurements, indicating a very repeatable system, particularly in measurement of cutting forces.
4. Statistical analysis of the experiment results involves conducting a Bartlett's test for homogeneity of variance and a *t*-test to determine statistical differences. When a *t*-test with α=0.05 was used for analysis with 5 replicates of each individual test, the testbed was found to be able to determine differences in torque with a sensitivity of 1-2.9%, thrust with a sensitivity of 1.4-2.5%, and temperature with a sensitivity of 2.7-8.2% with the specific sensitivity depending on the testing conditions.

3. EVALUATION OF FLUIDS BY SECOND GENERATION TESTBED

The second objective of this project was to evaluate ten MWFs in terms of cooling and lubricity using the second generation testbed. No single drilling condition can simulate all the cases encountered in industrial uses. For instance, drilling is usually carried out over a range of feedrates and cutting speeds [12]. Furthermore, various materials can be used for workpieces or drills. For example, drills can be carbide or steel and workpieces can be a wide variety of materials ranging from ferrous and non-ferrous metals to plastics. Thus, a single drilling experiment using a single workpiece material is not sufficient to completely characterize the performance of MWFs.

Previous research has shown that the performance of given MWFs can change under different cutting conditions [12]. To account for these changes, four separate experimental conditions were used to evaluate the cooling and lubricity performance of the MWFs. These experiments were designed to examine both the differences in performance of the various MWFs under varying conditions of cutting parameters, workpiece material, and dilutent source, and the ability of the second generation testbed methodology to detect differences when they are known to be present from independent experimental results found in the literature. The conditions used in the four experiments are provided in Table 3. They are identified as Finish 1018, Rough 1018, Rough 4340 and Rough 1018 Tap Water drilling experiments.

The experiments were designed to allow three types of analysis:

1. Comparison of fluids within type and experiment, e.g., two synthetic fluids in the Rough 1018 experiment;
2. Comparison between fluid types within experiment, e.g., synthetic fluids and soluble oils in the Rough 1018 experiment;
3. Comparison of fluids and types between experiments, e.g., a soluble oil in Finish 1018 and Rough 1018.

Table 3. Conditions for Four Separate Drilling Experiments

Experiment	**Rough 1018**	**Rough 4340**	**Finish 1018**	**Rough 1018 Tap Water**
Feedrate	0.1778 mm/rev	0.1778 mm/rev	0.1016 mm/rev	0.1778 mm/rev
Cutting speed	33.515 m/min	33.515 m/min	33.515 m/min	33.515 m/min
Workpiece	AISI 1018	AISI 4340	AISI 1018	AISI 1018
Hardness	167 HB	197 HB	167 HB	167 HB
MWF Concentration	10%	10%	10%	10%
Dilutent	Deionized water	Deionized water	Deionized water	Tap water

Table 3 and Figure 12 show how the analysis outlined above can be accomplished. According to Table 3, by comparing the Finish 1018 experiment and the Rough 1018 experiment, the feedrate effect can be seen. Likewise, by comparing the Rough 1018 experiment and the Rough 4340 experiment, the workpiece material effect can be observed. The compositions of the two workpiece steels are provided in Table 4. By comparing the Rough 1018 experiment and the Rough 1018 Tap Water experiment, the dilutent effect can be observed.

3.1 Fluid Choice for Performance Testing

MWFs from several different suppliers were chosen for testing. These included soluble oils, semi-synthetic, and synthetics. Conversations with large manufacturing facilities and smaller machining shops in Illinois were instrumental in choosing the fluids. Ten MWFs including four synthetic fluids, four semi-synthetic fluids, and two soluble oil fluids were chosen. Their brand names are listed in Table 5 along with their relative costs. The value 1.0 equals the lowest price and other prices are multiples of that.

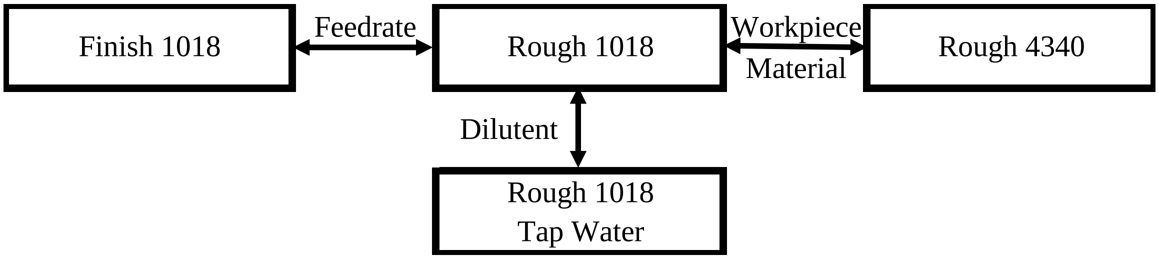

Figure 12. Design of Experiments

Table 4. Composition of AISI 1018 and AISI 4340

AISI 1018		AISI 4340	
Element	Weight %	Element	Weight %
C	0.15-0.20	C	0.38-0.43
Mn	0.60-0.90	Mn	0.60-0.80
P	0.04 (max)	P	0.035 (max)
S	0.05 (max)	S	0.04 (max)
		Si	0.15-0.30
		Cr	0.70-0.90
		Ni	1.65-2.00
		Mo	0.20-0.30

Table 5. Ten MWFs analyzed in this Study

Type	MWFs	Relative Price
Soluble oil	Master Chemical TRIM E206	1.89
	Hangsterfers S-500	1.96
Semi-synthetic	Castrol Clearedge 6510	1.00
	Castrol Clearedge 6519	1.00
	Environmental Lubricant Manufacturing Soyeasy Cool XXL	2.03
	Master Chemical TRIM SC230	1.59
Synthetic	Milacron Cimtech 310	2.65
	Master Chemical TRIM 229	2.68
	Master Chemical TRIM C270	1.59
	Nalco Tech Cool 35075	6.19

Trim E206 is a soluble oil coolant that, according to its manufacturer, performs well in a wide range of machining operations on ferrous and nonferrous materials. The recommended concentration range for E206 is 3%-10%. Hangsterfers S-500, the other soluble MWF chosen, is designed to be a non-toxic, non-irritating, and non-corrosive water soluble oil that is also amine-free, phosphate-free, and nitrite-free. Recommended concentration range for S-500 is 5%-10%. It is designed for use with a wide range of materials including all types of steel.

Castrol Clearedge 6510 is a semi-synthetic cutting and grinding fluid for ferrous metals. This fluid is stated by its manufacturer to offer good hard water stability. The recommended concentration range for 6510 is 5-8%. Castrol Clearedge 6519 is intended for aluminum machining but also provides premium performance in ferrous applications. The concentration range for 6519 is 5-8%. SoyEasyCool XXL, another semi-synthetic, is recommended for ferrous material, cast iron, and aluminum. It is designed using biotech-based technology, formulated with vegetable oils. The recommended concentration range for XXL is 5%-10%. TRIM SC230 is a semi-synthetic compatible with a very wide range of materials including cast iron, steels, and copper alloys as well as plastics and composites. The recommended concentration range for SC230 is 5%-10%.

CIMTECH 310 is a low pH synthetic fluid designed for the aerospace industry. The recommended concentration range for 310 is 5%-10%. TRIM 229 is a synthetic coolant designed to deliver good chemical corrosion inhibition on ferrous materials and is used mainly in surface grinding where maximum cooling and minimum foam are desirable. The recommended concentration range for 229 is 0.5%-2%. TRIM C270 is a synthetic fluid providing good corrosion inhibition on all common ferrous and nonferrous alloys. The recommended concentration range for C270 is 5%-10%. Tech Cool 35075 is designed to resist bacteria growth regardless of the system type or metal substrate. It is formulated for use on aluminum, steel and other alloys. The recommended concentration range for 35075 is 5-10%.

When deciding on the concentration percentage of MWF to use for the experiments, it was assumed that it might be easier to detect any differences in performance at higher concentrations of MWFs. While MWF manufacturers provide varying ranges of acceptable concentrations, to keep conditions as controlled as possible, a single value of 10% was chosen for the concentration of the MWFs used in the drilling experiments. Due to funding constraints, it was not possible to conduct experiments at various concentrations.

3.2 Experimental Results

The results for each experiment listed in Table 3 are presented in the following subsections. Each table in the subsections below consists of the experimental results broken down by fluid type and within each fluid type. The average statistic provided is the arithmetic mean of the five replicates conducted for that individual test. The complete set of raw data for all four experimental conditions is contained in Appendix A. The coefficient of variation column was calculated using the method provided in Section 2.3.

3.2.1 Rough 1018 Drilling Experiment Results

The results of the Rough 1018 drilling experiment are shown in Table 6. The drilling conditions used in the experiment were a feedrate of 0.1778 mm/rev and cutting speed of 33.515 m/min. The workpiece material was AISI 1018 steel and the fluids were used at a 10% concentration diluted with deionized water. The high level of repeatability is confirmed through the low coefficients of variation reported in Table 6. The largest coefficient of variation found through testing ten fluids for five replicates each was 0.031 for the cutting forces and 0.092 for the temperature measurements, which indicates a repeatable system.

Table 6. Rough 1018 Drilling Experiment Results

Type	Fluid	Average	Standard deviation	COV
Soluble oil	**E206**			
	Torque (N m)	10.84	0.16	0.015
	Thrust (N)	2626	33.86	0.013
	Temperature (°C)	69.34	5.63	0.081
	S-500			
	Torque (N m)	10.56	0.20	0.019
	Thrust (N)	2568.2	33.48	0.013
	Temperature (°C)	71.98	2.33	0.032
Semi-synthetic	**6510**			
	Torque (N m)	10.45	0.22	0.021
	Thrust (N)	2554	42.24	0.017
	Temperature (°C)	67.86	3.59	0.053
	6519			
	Torque (N m)	10.49	0.20	0.019
	Thrust (N)	2573.8	48.78	0.019
	Temperature (°C)	66.98	3.31	0.049
	XXL			
	Torque (N m)	10.36	0.25	0.024
	Thrust (N)	2531	48.22	0.019
	Temperature (°C)	73.62	5.52	0.075
	SC230			
	Torque (N m)	10.24	0.16	0.015
	Thrust (N)	2510.8	23.11	0.010
	Temperature (°C)	77.06	4.67	0.061
Synthetic	**310**			
	Torque (N m)	9.85	0.29	0.029
	Thrust (N)	2425	65.72	0.027
	Temperature (°C)	74.08	4.82	0.065
	229			
	Torque (N m)	10.62	0.32	0.031
	Thrust (N)	2505.4	11.63	0.005
	Temperature (°C)	72.48	1.85	0.026
	C270			
	Torque (N m)	10.42	0.16	0.016
	Thrust (N)	2505.6	27.15	0.011
	Temperature (°C)	78.34	1.00	0.013
	35075			
	Torque (N m)	10.78	0.19	0.018
	Thrust (N)	2580.2	11.03	0.004
	Temperature (°C)	70.78	6.49	0.092

A Bartlett's test [14] was conducted for each of the torque, thrust, and temperature data sets. The Bartlett's test showed that, for α = 0.01, homogeneity of variance could be assumed for all three responses; torque, thrust, and temperature. Therefore, pooled variance estimates for each response were used to determine statistical differences within the Rough 1018 experiment.

3.2.2 Rough 4340 Drilling Experiment Results

The drilling conditions for the Rough 4340 experiment were a feedrate of 0.1778 mm/rev and cutting speed of 33.515 m/min. The workpiece material was AISI 4340 steel and the fluids were used at a 10% concentration diluted with deionized water. The effect of workpiece composition on MWF performance can be determined when the result of the Rough 1018 experiment is compared with the result when using an AISI 4340 steel workpiece. The results of the Rough 4340 drilling experiment are shown in Table 7. The high level of repeatability is confirmed through the low coefficients of variation in Table 7. The largest coefficient of variation found through testing ten fluids for five replicates each was 0.026 for the cutting forces and 0.035 for the temperature measurements.

A Bartlett's test [14] was conducted for each of the torque, thrust, and temperature data sets. The Bartlett's test showed that, for α = 0.01, homogeneity of variance could be assumed for all three responses; torque, thrust, and temperature. Therefore, pooled variance estimates of each response were used to determine statistical differences within the Rough 4340 experiment.

Table 7. Rough 4340 Drilling Experiment Results

Type	Fluid	Average	Standard deviation	COV
Soluble oil	**E206**			
	Torque (N m)	10.91	0.05	0.005
	Thrust (N)	2543.8	36.23	0.014
	Temperature (°C)	71.06	1.11	0.016
	S-500			
	Torque (N m)	10.87	0.03	0.002
	Thrust (N)	2529	21.18	0.008
	Temperature (°C)	73.7	0.99	0.013
Semi-synthetic	**6510**			
	Torque (N m)	10.87	0.03	0.003
	Thrust (N)	2540.2	10.62	0.004
	Temperature (°C)	68.24	1.10	0.016
	6519			
	Torque (N m)	10.88	0.05	0.005
	Thrust (N)	2552.4	18.85	0.007
	Temperature (°C)	68.04	2.10	0.031
	XXL			
	Torque (N m)	10.76	0.05	0.005
	Thrust (N)	2559.4	21.49	0.008
	Temperature (°C)	68.4	1.47	0.021
	SC230			
	Torque (N m)	10.89	0.03	0.003
	Thrust (N)	2563.2	18.66	0.007
	Temperature (°C)	69.18	1.26	0.018
Synthetic	**310**			
	Torque (N m)	10.69	0.13	0.013
	Thrust (N)	2515.6	43.15	0.017
	Temperature (°C)	72.82	2.58	0.035
	229			
	Torque (N m)	10.96	0.14	0.013
	Thrust (N)	2473.8	64.94	0.026
	Temperature (°C)	73.6	1.83	0.025
	C270			
	Torque (N m)	10.82	0.11	0.010
	Thrust (N)	2501.4	23.73	0.009
	Temperature (°C)	74.36	0.83	0.011
	35075			
	Torque (N m)	10.67	0.11	0.010
	Thrust (N)	2466	24.47	0.010
	Temperature (°C)	75.98	1.77	0.023

3.2.3 Finish 1018 Drilling Experiment Results

The results of the Finish 1018 drilling experiment are provided in Table 8. The drilling conditions for the experiment were a feedrate of 0.1016 mm/rev and cutting speed of 33.515 m/min. The workpiece material was AISI 1018 steel and the fluids were used at a 10% concentration diluted with deionized water. When compared with the Rough 1018 drilling experiment results, this experiment showed how the fluids performed at different feedrates. The high level of repeatability of the testbed is confirmed through the low coefficients of variation in Table 8. The largest coefficient of variation found through testing ten fluids for five replicates each was 0.037 for the cutting forces and 0.059 for the temperature measurements.

A Bartlett's test [14] was conducted for each of the torque, thrust, and temperature data sets in the Finish 1018 experiment. The Bartlett's test showed that, for $\alpha = 0.01$, homogeneity of variance could be assumed for all three responses; torque, thrust, and temperature. Therefore, pooled variance estimates of each response were used to determine statistical differences within the Finish 1018 experiment.

Table 8. Finish 1018 Drilling Experiment Results

Type	Fluid	Average	Standard deviation	COV
Soluble oil	**E206**			
	Torque (N m)	7.23	0.05	0.006
	Thrust (N)	1741.8	12.77	0.007
	Temperature (°C)	67.64	3.43	0.051
	S-500			
	Torque (N m)	7.22	0.05	0.008
	Thrust (N)	1734	30.93	0.018
	Temperature (°C)	69	2.91	0.042
Semi-synthetic	**6510**			
	Torque (N m)	7.25	0.09	0.013
	Thrust (N)	1695.8	14.39	0.008
	Temperature (°C)	67.64	3.43	0.051
	6519			
	Torque (N m)	7.27	0.18	0.025
	Thrust (N)	1703.4	30.79	0.018
	Temperature (°C)	64.56	3.02	0.047
	XXL			
	Torque (N m)	7.05	0.07	0.010
	Thrust (N)	1681	39.41	0.023
	Temperature (°C)	67.28	3.96	0.059
	SC230			
	Torque (N m)	7.24	0.05	0.007
	Thrust (N)	1713.2	11.52	0.007
	Temperature (°C)	65.72	2.60	0.040
Synthetic	**310**			
	Torque (N m)	7.07	0.04	0.006
	Thrust (N)	1637.2	33.95	0.021
	Temperature (°C)	66.38	2.23	0.034
	229			
	Torque (N m)	7.47	0.06	0.008
	Thrust (N)	1704.4	21.23	0.012
	Temperature (°C)	68.02	3.14	0.046
	C270			
	Torque (N m)	7.11	0.16	0.023
	Thrust (N)	1686.6	61.96	0.037
	Temperature (°C)	65.72	1.93	0.029
	35075			
	Torque (N m)	7.23	0.05	0.007
	Thrust (N)	1690.4	23.18	0.014
	Temperature (°C)	66.42	1.87	0.028

3.2.4 Rough 1018 Tap Water Drilling Experiment Results

The results of the Rough 1018 Tap Water drilling experiment are shown in Table 9. The drilling conditions for the experiment were a feedrate of 0.1778 mm/rev and cutting speed of 33.515 m/min. The workpiece material was AISI 1018 steel and the fluids were used at a 10% concentration diluted with Champaign County, Illinois, tap water. When compared with the results of the Rough 1018 experiment (Table 6), the effect of tap water versus deionized water on the performance of the MWFs can be determined. Previously published results [13, 3] have shown that water hardness can significantly impact MWF performance. However, the tap water in the current experiments was only mildly hard, with a hardness value of 75-85 ppm (as $CaCO_3$). The high level of repeatability is confirmed through the low coefficients of variation in Table 9. The largest coefficient of variation found through testing ten fluids for five replicates each was 0.024 for the cutting forces and 0.081 for the temperature measurements.

A Bartlett's test [14] was conducted for each of the torque, thrust, and temperature data sets in the Rough 1018 Tap Water experiment. The Bartlett's test showed that, for α = 0.01, homogeneity of variance could be assumed for torque, thrust, and temperature. Therefore, pooled variance estimates for each response were used to determine statistical differences in all of the experimental results.

Table 9. Rough 1018 Tap Water Drilling Experiment Results

Type	Fluid	Average	Standard deviation	COV
Soluble oil	**E206**			
	Torque (N m)	10.24	0.09	0.009
	Thrust (N)	2509.6	14.09	0.005
	Temperature (°C)	74.41	5.86	0.07
	S-500			
	Torque (N m)	10.07	0.20	0.019
	Thrust (N)	2475.6	31.19	0.012
	Temperature (°C)	74.12	1.30	0.017
Semi-synthetic	**6510**			
	Torque (N m)	10.07	0.17	0.016
	Thrust (N)	2446.7	30.06	0.012
	Temperature (°C)	76.44	3.80	0.049
	6519			
	Torque (N m)	10.14	0.11	0.01
	Thrust (N)	2466.6	28.88	0.011
	Temperature (°C)	71.69	4.72	0.065
	XXL			
	Torque (N m)	9.98	0.16	0.015
	Thrust (N)	2430.9	32.64	0.013
	Temperature (°C)	74.15	3.02	0.04
	SC230			
	Torque (N m)	10.01	0.24	0.024
	Thrust (N)	2416.2	23.01	0.009
	Temperature (°C)	78.13	4.06	0.052
Synthetic	**310**			
	Torque (N m)	9.86	0.19	0.019
	Thrust (N)	2386.7	26.81	0.011
	Temperature (°C)	80.04	6.53	0.081
	229			
	Torque (N m)	10.13	0.10	0.01
	Thrust (N)	2442.6	20.85	0.008
	Temperature (°C)	78.68	4.75	0.06
	C270			
	Torque (N m)	9.82	0.13	0.013
	Thrust (N)	2381.5	27.69	0.011
	Temperature (°C)	77.13	2.68	0.034
	35075			
	Torque (N m)	10.15	0.18	0.017
	Thrust (N)	2477.1	37.22	0.015
	Temperature (°C)	72.68	3.91	0.053

The pooled variances for each response type and each experiment are provided in Table 10. It may be noted that, although each response type within each experiment met the homogeneity of variance criteria, the variance did change a significant amount between experiments. For example, torque pooled variance values varied from 498.85 for the Rough 1018 experiment to 73.32 for the Rough 4340 experiment. The only response type that had relatively close variances between experiments was thrust.

3.3 Statistical Analysis of Each Drilling Experiment

The experimental results for each fluid presented in Tables 6-9 were compared to each other using a pairwise two-tailed *t*-test with $\alpha = 0.05$ and using the pooled variance based on the Bartlett's test results in Section 3.2. Comparison results are provided in the following subsections in the form of a fluid matrix where each fluid pair is identified as "N", meaning not statistically different, or "D", meaning statistically different.

When interpreting the results of the comparisons, we assumed that torque and thrust values are primarily, but not entirely, a reflection of lubrication performance, while temperature values are reflective of cooling performance. We acknowledge that the situation is actually more complex than this. But it is fair to say that the use of both cutting forces and temperature enabled us to shed more light on the separate lubrication and cooling performance characteristics of the various MWFs than if only cutting forces alone were used.

Table 10. Pooled Variance Values for Four Experimental Conditions

Test	Response	Pooled Variance Estimate
Rough 1018	Torque (N m)	0.0499
	Thrust (N)	1460.4
	Temperature (ºC)	18.3
Rough 4340	Torque (N m)	0.0073
	Thrust (N)	1028
	Temperature (ºC)	2.54
Finish 1018	Torque (N m)	0.0088
	Thrust (N)	994.04
	Temperature (ºC)	8.56
Rough 1018 Tap Water	Torque (N m)	0.0267
	Thrust (N)	780.94
	Temperature (ºC)	18.6

3.3.1 Rough 1018 Drilling Experiment Results

The statistical analysis for comparisons of fluids within the Rough 1018 experiment is provided in Tables 11-13. Table 11 shows the comparison results for the torque response. It reveals that no statistical difference was found within the two soluble oil MWFs, E206 and S-500. Within semi-synthetic MWFs, there were no differences detected. Within synthetic MWFs, 310 was statistically different from the other three synthetic MWFs and C270 was different from 35075.

The thrust response comparisons for the Rough 1018 experiment are provided in Table 12. Within the soluble oil MWFs tested, the thrust response of E206 was different statistically from S-500. Within semi-synthetic MWFs, no differences could be statistically determined except between SC230 and 6519. Within synthetic MWFs, 310 was different statistically from the other three synthetic MWFs, which was the same result as from the torque statistical test. The MWF 35075 was also statistically different than the three other synthetics.

The statistical comparisons for temperature response in the Rough 1018 experiment are provided in Table 13. These results show that there was no statistical difference between the two soluble oils tested. Semi-synthetic MWFs can be divided into two groups where one is XXL and SC230 and the other is Castrol Clearedge (6510 and 6519). Within synthetic MWFs, only C270 was different statistically from 229 and 35075.

Table 11. Rough 1018 Drilling Experiment Torque Statistical Analysis

Type		Soluble oil		Semi-synthetic				Synthetic			
		E206	S500	6510	6519	XXL	SC230	310	229	C270	35075
Soluble oil	E206		N	D	D	D	D	D	N	D	N
	S-500	N		N	N	N	D	D	N	N	N
Semi-synthetic	6510	D	N		N	N	N	D	N	N	D
	6519	D	N	N		N	N	D	N	N	D
	XXL	D	N	N	N		N	D	N	N	D
	SC230	D	D	N	N	N		D	D	N	D
Synthetic	310	D	D	D	D	D	D		D	D	D
	229	N	N	N	N	N	D	D		N	N
	C270	D	N	N	N	N	N	D	N		D
	35075	N	N	D	D	D	D	D	N	D	

(N= Not statistically different, D= Statistically different)

Table 12. Rough 1018 Drilling Experiment Thrust Statistical Analysis

Type		Soluble oil		Semi-synthetic				Synthetic			
		E206	**S500**	**6510**	**6519**	**XXL**	**SC230**	**310**	**229**	**C270**	**35075**
Soluble oil	**E206**		D	D	D	D	D	D	D	D	N
	S-500	D		N	N	N	D	D	D	D	N
Semi-synthetic	**6510**	D	N		N	N	N	D	N	N	N
	6519	D	N	N		N	D	D	D	D	N
	XXL	D	N	N	N		N	D	N	N	D
	SC230	D	D	N	D	N		D	N	N	D
Syntehtic	**310**	D	D	D	D	D	D		D	D	D
	229	D	D	N	D	N	N	D		N	D
	C270	D	D	N	D	N	N	D	N		D
	35075	N	N	N	N	D	D	D	D	D	

(N= Not statistically different, D= Statistically different)

Table 13. Rough 1018 Drilling Experiment Temperature Statistical Analysis

Type		Soluble oil		Semi-synthetic				Synthetic			
		E206	**S500**	**6510**	**6519**	**XXL**	**SC230**	**310**	**229**	**C270**	**35075**
Soluble oil	**E206**		N	N	N	N	D	N	N	D	N
	S-500	N		N	N	N	N	N	N	D	N
Semi-synthetic	**6510**	N	N		N	D	D	D	N	D	N
	6519	N	N	N		D	D	D	D	D	N
	XXL	N	N	D	D		N	N	N	N	N
	SC230	D	N	D	D	N		N	N	N	D
Synthetic	**310**	N	N	D	D	N	N		N	N	N
	229	N	N	N	D	N	N	N		D	N
	C270	D	D	D	D	N	N	N	D		D
	35075	N	N	N	N	N	D	N	N	D	

(N= Not statistically different, D= Statistically different)

The Rough 1018 experiment results from Table 6 are combined with the statistical difference results in Tables 11-13 to provide the data sets and error bars presented in Figs. 13-15. Each error bar represents a 95% confidence interval for the true mean.

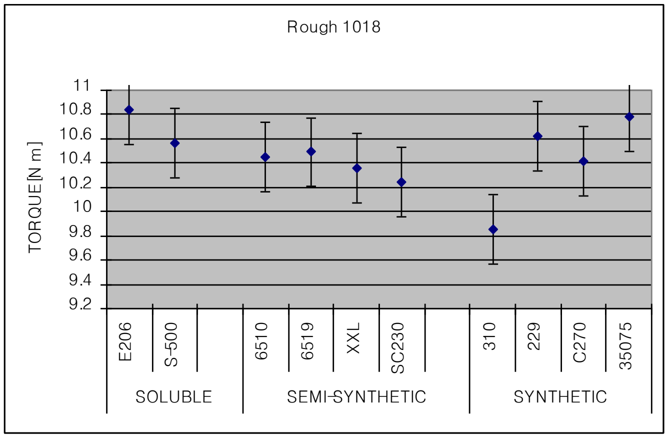

Figure 13. Rough 1018 Drilling Experiment Torque Results

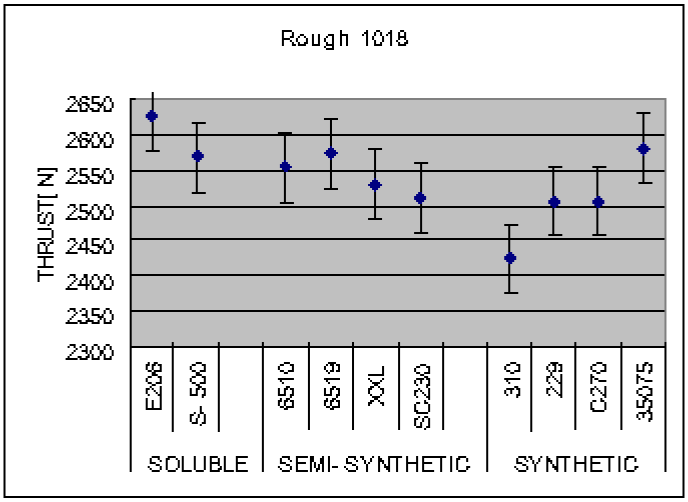

Figure 14. Rough 1018 Drilling Experiment Thrust Results

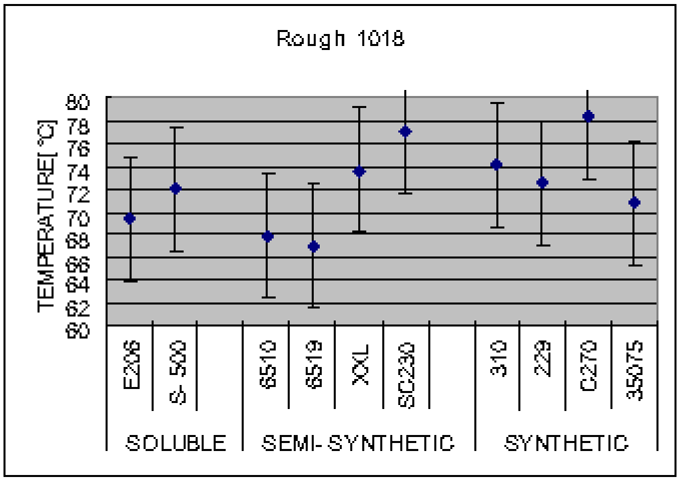

Figure 15. Rough 1018 Drilling Experiment Temperature Results

Within MWF Type Conclusions for Rough 1018

When comparing individual fluids within fluid types from the Rough 1018 experiment, the conclusions were:

- Within the soluble oil type, S-500 had a lower magnitude of thrust than E206 while no difference was present in the torque or temperature responses.
- The semi-synthetic MWFs were tightly grouped in terms of torque and thrust except for SC230, which had the lowest average value.
- In terms of semi-synthetic temperature response, the two Castrol fluids (6510 and 6519) had significantly lower magnitudes than the non-Castrol semi-synthetics (XXL and SC230).
- Synthetic fluid 310 had the lowest measured torque and thrust values of any fluid tested.
- Synthetic fluid 35075 had the highest cutting forces measured among the synthetic fluids although it also had the lowest temperature value.
- Synthetic fluid C270 provided the highest value in terms of temperature. In general, synthetic fluids are used because of their superior cooling ability, so the poor performance of C270 could point to a complicating factor in cooling beyond the percentage of water present in the fluid.

Between MWF Type Conclusions for Rough 1018

The following conclusions were reached when comparing between fluid types in the Rough 1018 experiment:

- In general, the soluble oils were shown to have the highest torque and thrust values while performing relatively well in the temperature response. This is an interesting observation because soluble oils are often chosen for their lubrication properties rather than their cooling properties.

- The fluids with the highest magnitude in terms of temperature were a synthetic fluid (C270) and a semi-synthetic fluid (SC230), with values higher than all other MWFs.
- The largest range of responses was seen in the synthetic fluids. This could be due to the large variety of value additives that are included in synthetic fluids and the unknown impact they may have on cutting forces and temperature.

The collective results of the Rough 1018 experiment are presented in Table 14. This table provides a matrix of the fluids and their relative responses for each test response. Results in Table 14 are delineated as High, Medium, or Low, where "High" means relatively good performance. For example, a fluid with a low magnitude of thrust relative to the other fluids would garner a "High" label in the appropriate box in Table 14. Fluids marked "High" had average values that fell within the 95% confidence interval of the fluid with the lowest value. This method is the same for all three test responses: torque, thrust, and temperature. Likewise, fluids marked "Low" had average values that fell within the 95% confidence interval of the highest value for the three test responses. All fluids not falling into either the "High" or the "Low" categories were marked as "Medium". For example, every fluid in Fig. 15 where the average falls within the error bar of the highest temperature value C270 (e.g., XXL, SC230, and 310) will be labeled as having "Low" temperature performance.

It should be pointed out that across any grouping of MWFs, including this grouping, formulation objectives will vary, so one must keep in mind that seemingly poor performance for one or more of the measures used here does not necessarily imply poor performance in general. For example, the use of synthetic fluid 35075 led to higher torque and thrust values, but one must keep in mind that a primary formulation objective for this MWF is bacteria growth inhibition, an objective not included in this comparison.

3.3.2 Rough 4340 Drilling Experiment Results

The statistical analysis for comparisons of fluids within the Rough 4340 experiment is provided in Tables 15-17. Table 15 gives the comparison results for the torque response. It shows that the soluble oil MWFs were not statistically different from each other in the Rough 4340 experiment.

Table 14. Summary of Results for Rough 1018 Experiment

MWF		Soluble oil		Semi-synthetic				Synthetic			
		E206	S-500	6510	6519	XXL	SC230	310	229	C270	35075
Rough 1018	Torque	L	L	M	M	M	M	H	L	M	L
	Thrust	L	M	M	M	M	M	H	M	M	L
	Temperature	H	H	H	H	L	L	L	M	L	H

(L= Low, M= Medium, H= High)

Within the semi-synthetic MWFs, XXL was statistically different from SC230 and 6519. Within synthetic MWFs, 310 and 35075 were different from 229 and C270.

The statistical comparison results for the thrust response of the Rough 4340 experiment are provided in Table 16. It shows that soluble oil MWFs cannot be statistically differentiated from each other in magnitude of thrust. Within semi-synthetic MWFs there were no statistically significant differences. Within synthetic MWFs, 310 was statistically different from 35075 and 229.

Table 15. Rough 4340 Drilling Experiment Torque Statistical Analysis

Type		Soluble oil		Semi-synthetic				Synthetic			
		E206	S500	6510	6519	XXL	SC230	310	229	C270	35075
Soluble oil	E206		N	N	N	D	N	D	N	N	D
	S-500	N		N	N	N	N	D	N	N	D
Semi-synthetic	6510	N	N		N	N	N	D	N	N	D
	6519	N	N	N		D	N	D	N	N	D
	XXL	D	N	N	D		D	N	D	N	N
	SC230	N	N	N	N	D		D	N	N	D
Synthetic	310	D	D	D	D	N	D		D	D	N
	229	N	N	N	N	D	N	D		D	D
	C270	N	N	N	N	N	N	D	N		D
	35075	D	D	D	D	N	D	N	D	D	

(N= Not statistically different, D= Statistically different)

Table 16. Rough 4340 Drilling Experiment Thrust Statistical Analysis

Type		Soluble oil		Semi-synthetic				Synthetic			
		E206	**S500**	**6510**	**6519**	**XXL**	**SC230**	**310**	**229**	**C270**	**35075**
Soluble oil	**E206**		N	N	N	N	N	N	D	D	D
	S-500	N		N	N	N	N	N	D	N	D
Semi-sytnehtic	**6510**	N	N		N	N	N	N	D	N	D
	6519	N	N	N		N	N	N	D	D	D
	XXL	N	N	N	N		N	D	D	D	D
	SC230	N	N	N	N	N		D	D	D	D
Synthetic	**310**	N	N	N	N	D	D		D	N	D
	229	D	D	D	D	D	D	D		N	N
	C270	D	N	N	D	D	D	N	N		N
	35075	D	D	D	D	D	D	D	N	N	

(N= Not statistically different, D= Statistically different)

The statistical comparison results for the temperature response of the Rough 4340 experiment are provided in Table 17. Table 17 shows that, unlike the results of torque and thrust responses, soluble oil MWFs were different statistically from each other. There were no statistically significant differences within semi-synthetic MWFs. Within synthetic MWFs, 35075 had a statistically higher temperature magnitude than 310 and 229.

The Rough 4340 experiment results from Table 7 are combined with the statistical difference results in Tables 15-17 to provide the data sets and error bars presented in Figs. 16-18. Each error bar represents a 95% confidence interval for the mean.

Table 17. Rough 4340 Drilling Experiment Temperature Statistical Analysis

Type		Soluble oil		Semi-synthetic				Synthetic			
		E206	**S500**	**6510**	**6519**	**XXL**	**SC230**	**310**	**229**	**C270**	**35075**
Soluble	**E206**		D	D	D	D	N	N	D	D	D
	S-500	D		D	D	D	D	N	N	N	D
Semi-synthetic	**6510**	D	D		N	N	N	D	D	D	D
	6519	D	D	N		N	N	D	D	D	D
	XXL	D	D	N	N		N	D	D	D	D
	SC230	N	D	N	N	N		D	D	D	D
Synthetic	**310**	N	N	D	D	D	D		N	N	D
	229	D	N	D	D	D	D	N		N	D
	C270	D	N	D	D	D	D	N	N		N
	35075	D	D	D	D	D	D	D	D	N	

(N= Not statistically different, D= Statistically different)

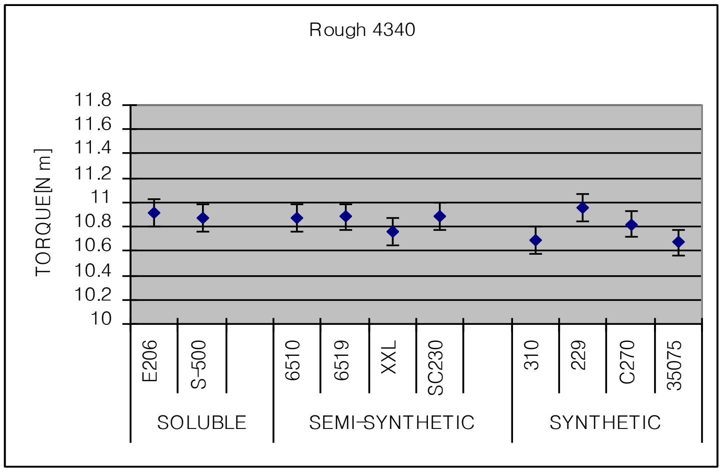

Figure 16. Rough 4340 Drilling Experiment Torque Results

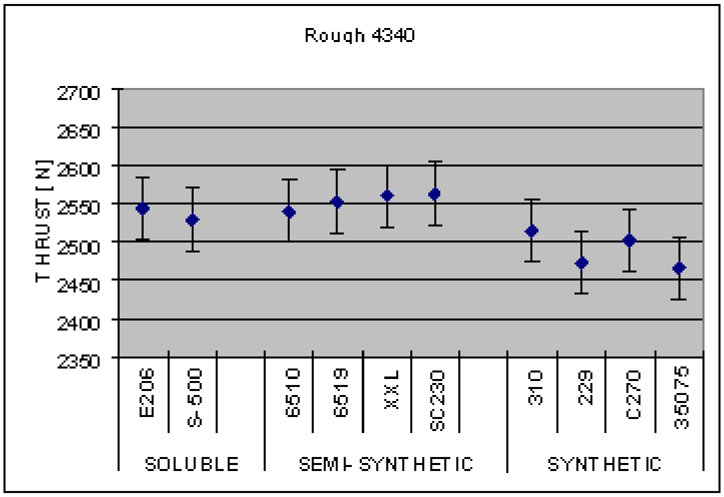

Figure 17. Rough 4340 Drilling Experiment Thrust Results

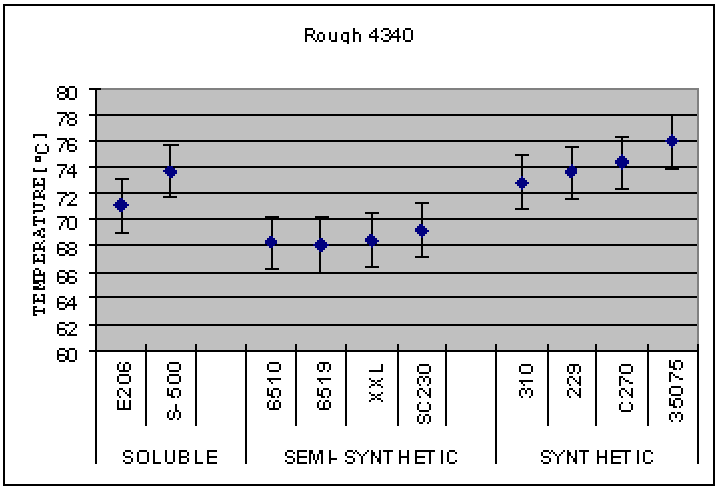

Figure 18. Rough 4340 Drilling Experiment Temperature Results

Within MWF Type Conclusions for Rough 4340

From the Rough 4340 experiment, the following conclusions were reached about individual fluids when comparing within fluid types:

- Within the soluble oil type, E206 had a lower temperature magnitude than S-500 but there was no statistical difference in cutting force magnitudes.
- In the semi-synthetic fluids, SoyEasyCool XXL had a significantly lower torque magnitude than the majority of the other semi-synthetic MWFs.
- All semi-synthetic fluids behaved statistically similarly in terms of thrust and temperature magnitudes.
- The synthetic fluid 35075 behaved well in torque and thrust measurements but was higher than all other synthetic MWFs in temperature response.

Between MWF Type Conclusions for Rough 4340

When comparing between fluid types in the Rough 4340 experiment, the conclusions were:

- The semi-synthetic fluids maintained a tight grouping. Only one fluid was statistically different in magnitude of torque. However, the range in values was relatively small compared to the range in values for the synthetic fluids.
- The fluids with the lowest magnitudes in torque and thrust were both synthetics, while the fluids with the lowest temperature magnitudes were semi-synthetics.
- In general, the synthetic MWFs had thrust values significantly lower than soluble oil MWFs and semi-synthetic MWFs.
- All semi-synthetic MWFs were found to provide temperature magnitudes statistically lower than synthetic MWFs and soluble oil MWFs.

The collective results of the Rough 4340 experiment are presented in Table 18. This table provides a matrix of the fluids and their relative responses for each test response. Table 18 is read in the same way as described for Table 14 in Section 3.3.1.

3.3.3 Finish 1018 Drilling Experiment Results

The statistical analysis for comparisons of fluids within the Finish 1018 experiment is provided in Tables 19-21. Table 19 shows the comparison results for the torque response. There was no statistical difference within soluble oil MWFs. Within semi-synthetic MWFs, XXL was significantly different than the other three MWFs in terms of torque. Within synthetic MWFs, all pairs showed statistical differences except for the pair of 310 and C270 and the pair of 35075 and C270.

Table 18. Summary of Results for Rough 4340 Experiment

MWF		**Soluble oil**		**Semi-synthetic**				**Synthetic**			
		E206	**S-500**	**6510**	**6519**	**XXL**	**SC230**	**310**	**229**	**C270**	**35075**
Rough 4340	**Torque**	L	L	L	L	H	L	H	L	M	H
	Thrust	L	L	L	L	L	L	M	H	H	H
	Temperature	M	M	H	H	H	H	M	M	L	L

(L= Low, M= Medium, H= High)

Table 20 provides the statistical comparison results of the thrust response in the Finish 1018 experiment. It shows that, similar to the torque results, E206 was not different from S-500 in magnitude of thrust. There were also no statistically significant differences within semi-synthetic MWFs. Comparing the thrust magnitude of the synthetic MWFs, 310 was statistically different than the other three fluids.

Table 21 provides the statistical comparison results of the temperature response in the Finish 1018 experiment. It shows that there was no difference within any of the same type of MWF in terms of temperature magnitude. Furthermore, only a single pair of the total 45 fluid pairs showed a statistical difference between mean temperatures.

Table 19. Finish 1018 Drilling Experiment Torque Statistical Analysis

Type		**Soluble oil**		**Semi-synthetic**				**Synthetic**			
		E206	**S500**	**6510**	**6519**	**XXL**	**SC230**	**310**	**229**	**C270**	**35075**
Soluble oil	**E206**		N	N	N	D	N	D	D	D	N
	S-500	N		N	N	D	N	D	D	N	N
Semi-synthetic	**6510**	N	N		N	D	N	D	D	D	N
	6519	N	N	N		D	N	D	D	D	N
	XXL	D	D	D	D		D	N	D	N	D
	SC230	N	N	N	N	D		D	D	D	N
Synthetic	**310**	D	D	D	D	N	D		D	N	D
	229	D	D	D	D	D	D	D		D	D
	C270	D	N	D	D	N	D	N	D		N
	35075	N	N	N	N	D	N	D	D	N	

(N= Not statistically different, D= Statistically different)

Table 20. Finish 1018 Drilling Experiment Thrust Statistical Analysis

Type		Soluble oil		Semi-synthetic				Synthetic			
		E206	S500	6510	6519	XXL	SC230	310	229	C270	35075
Soluble oil	E206		N	D	N	D	N	D	N	D	D
	S-500	N		N	N	D	N	D	N	D	D
Semi-synthetic	6510	D	N		N	N	N	D	N	N	N
	6519	N	N	N		N	N	D	N	N	N
	XXL	D	D	N	N		N	D	N	N	N
	SC230	N	N	N	N	N		D	N	N	N
Synthetic	310	D	D	D	D	D	D		D	D	D
	229	N	N	N	N	N	N	D		N	N
	C270	D	D	N	N	N	N	D	N		N
	35075	D	D	N	N	N	N	D	N	N	

(N= Not statistically different, D= Statistically different)

Table 21. Finish 1018 Drilling Experiment Temperature Statistical Analysis

Type		Soluble oil		Semi-synthetic				Synthetic			
		E206	S500	6510	6519	XXL	SC230	310	229	C270	35075
Soluble oil	E206		N	N	N	N	N	N	N	N	N
	S-500	N		N	D	N	N	N	N	N	N
Semi-synthetic	6510	N	N		N	N	N	N	N	N	N
	6519	N	D	N		N	N	N	N	N	N
	XXL	N	N	N	N		N	N	N	N	N
	SC230	N	N	N	N	N		N	N	N	N
Synthetic	310	N	N	N	N	N	N		N	N	N
	229	N	N	N	N	N	N	N		N	N
	C270	N	N	N	N	N	N	N	N		N
	35075	N	N	N	N	N	N	N	N	N	

(N= Not statistically different, D= Statistically different)

The Finish 1018 experiment results from Table 8 are combined with the statistical difference results in Tables 19-21 to provide the data sets and error bars presented in Figs. 19-21. Each error bar represents a 95% confidence interval for the mean.

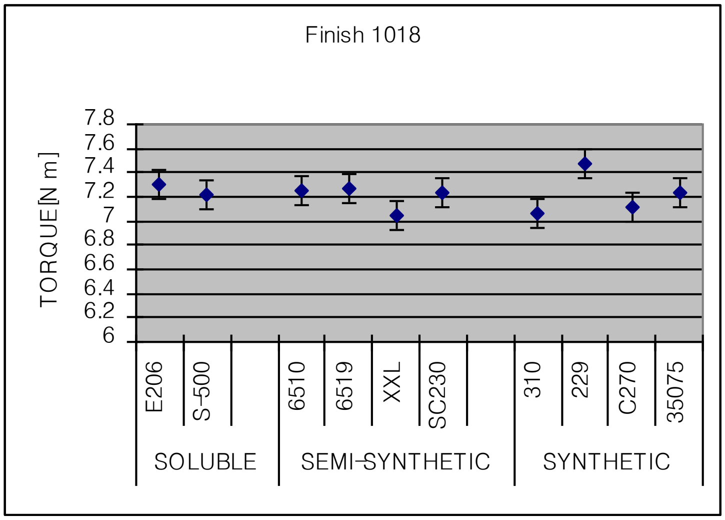

Figure 19. Finish 1018 Drilling Experiment Torque Results

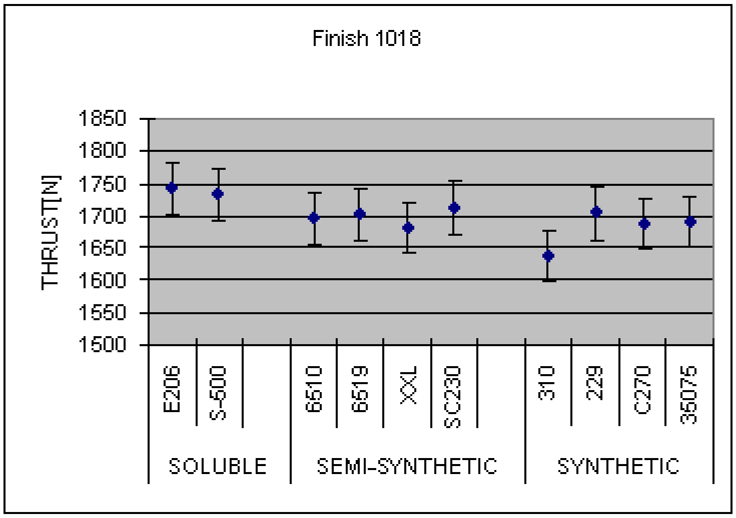

Figure 20. Finish 1018 Drilling Experiment Thrust Results

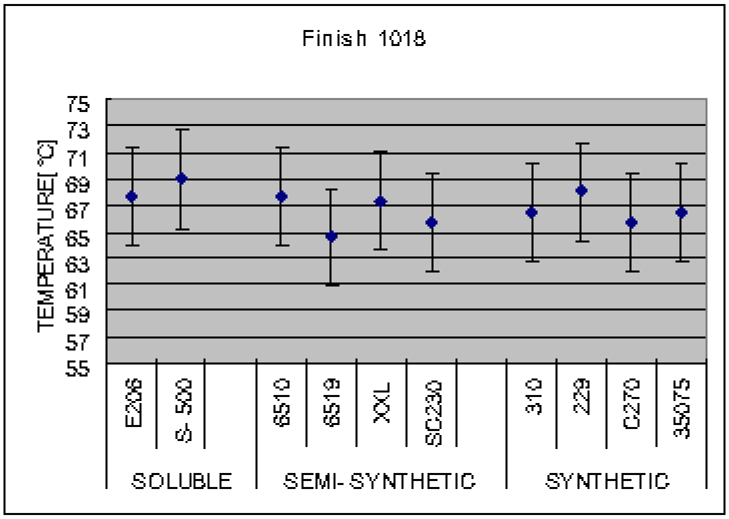

Figure 21. Finish 1018 Drilling Experiment Temperature Results

Within MWF Type Conclusions for Finish 1018

The conclusions about individual fluids from comparisons within fluid types from the Finish 1018 experiment were:

- No significant difference was determined in torque, thrust, or temperature responses within soluble oil MWFs.
- The vegetable oil-based semi-synthetic MWF XXL had a torque response significantly lower than the other three semi-synthetic MWFs.
- There were no statistical differences in terms of temperature within the synthetics, semi-synthetics, or soluble oils for the Finish 1018 experiment.
- Within the synthetic MWFs, 310 had lower torque and thrust responses than the other synthetic MWFs.

Between MWF Type Conclusions for Finish 1018

When comparing between fluid types, the following conclusions were reached from the Finish 1018 experiment:

- The synthetic fluid 229 had a statistically higher torque response than all other fluids across types. It should be noted that 229 is specifically formulated for grinding and is therefore designed with cooling rather than lubrication in mind and for use at concentrations below 2%.
- The synthetic fluid Milacron 310 had the lowest torque and thrust response values.
- In the thrust response, semi-synthetic MWFs were tightly grouped except for SC230 and they provided generally lower thrust values than the soluble oil MWFs.

Table 22. Summary of Results for Finish 1018 Experiment

MWF		Soluble oil		Semi-synthetic				Synthetic			
		E206	S-500	6510	6519	XXL	SC230	310	229	C270	35075
Finish 1018	**Torque**	M	M	M	M	H	M	H	L	H	M
	Thrust	L	L	M	L	M	L	H	L	M	M
	Temperature	L	L	L	H	L	L	L	L	L	L

(L= Low, M= Medium, H= High)

The collective results of the Finish 1018 experiment are presented in Table 22. This table provides a matrix of the fluids and their relative responses for each test response. Table 22 is read in the same way as described for Table 14 in Section 3.3.1.

3.3.4 Rough 1018 Tap Water Drilling Experiment Results

The results of the statistical analysis for the comparison of fluids within the Rough 1018 Tap Water experiment are provided in Tables 23-25. Table 23 gives the comparison results for the torque response. Table 23 shows that, within soluble oil MWFs, E206 was not statistically different from S-500. There was no significant statistical difference determined between semi-synthetic MWFs. In the synthetic MWFs group, the pair of 310 and C270 was statistically different from the pair of 229 and 35075.

Table 24 shows the statistical comparisons of the thrust values for the Rough 1018 Tap Water experiment. There were no statistical differences among the soluble oil fluids. In the semi-synthetic MWFs group, 6519 was statistically different from SC230. Of the synthetic MWFs, the only fluid pairs that were not significantly different were 310 and C270, and 229 and 35075, respectively.

Table 25 provides the statistical comparisons of the temperature values for the Rough 1018 Tap Water experiment. As shown in Table 25, there were no differences within the soluble oil MWFs in terms of temperature response. Of the semi-synthetic MWFs, the pair of 6519 and SC230 showed statistical difference. In the synthetic MWFs group, 35075 was different from 310 and 229.

Table 23. Rough 1018 Tap Water Drilling Experiment Torque Statistical Analysis

Type		Soluble oil		Semi-synthetic				Synthetic			
		E206	**S500**	**6510**	**6519**	**XXL**	**SC230**	**310**	**229**	**C270**	**35075**
Soluble oil	**E206**		N	N	N	D	D	D	N	D	N
	S-500	N		N	N	N	N	N	N	D	N
Semi-synthetic	**6510**	N	N		N	N	N	D	N	D	N
	6519	N	N	N		N	N	D	N	D	N
	XXL	D	N	N	N		N	N	N	N	N
	SC230	D	N	N	N	N		N	N	N	N
Synthetic	**310**	D	N	D	D	N	N		D	N	D
	229	N	N	N	N	N	N	D		D	N
	C270	D	D	D	D	N	N	N	D		D
	35075	N	N	N	N	N	N	D	N	D	

(N= Not statistically different, D= Statistically different)

Table 24. Rough 1018 Tap Water Drilling Experiment Thrust Statistical Analysis

Type		Soluble oil		Semi-synthetic				Synthetic			
		E206	**S500**	**6510**	**6519**	**XXL**	**SC230**	**310**	**229**	**C270**	**35075**
Soluble oil	**E206**		N	D	D	D	D	D	D	D	N
	S-500	N		N	N	D	D	D	N	D	N
Semi-synthetic	**6510**	D	N		N	N	N	D	N	D	N
	6519	D	N	N		N	D	D	N	D	N
	XXL	D	D	N	N		N	D	N	D	D
	SC230	D	D	N	D	N		N	N	N	D
Synthetic	**310**	D	D	D	D	D	N		D	N	D
	229	D	N	N	N	N	N	D		D	N
	C270	D	D	D	D	D	N	N	D		D
	35075	N	N	N	N	D	D	D	N	D	

(N= Not statistically different, D= Statistically different)

Table 25. Rough 1018 Tap Water Experiment Temperature Statistical Analysis

Type		Soluble oil		Semi-synthetic				Synthetic			
		E206	S500	6510	6519	XXL	SC230	310	229	C270	35075
Soluble oil	E206		N	N	N	N	N	D	N	N	N
	S-500	N		N	N	N	N	D	N	N	N
Semi-synthetic	6510	N	N		N	N	N	N	N	N	N
	6519	N	N	N		N	D	D	D	N	N
	XXL	N	N	N	N		N	D	N	N	N
	SC230	N	N	N	D	N		N	N	N	N
Synthetic	310	D	D	N	D	D	N		N	N	D
	229	N	N	N	D	N	N	N		N	D
	C270	N	N	N	N	N	N	N	N		N
	35075	N	N	N	N	N	N	D	D	N	

(N= Not statistically different, D= Statistically different)

The Rough 1018 Tap Water experiment results from Table 9 are combined with the statistical difference results in Tables 23-25 to provide the data sets and error bars presented in Figs. 22-24. Each error bar represents a 95% confidence interval for the mean.

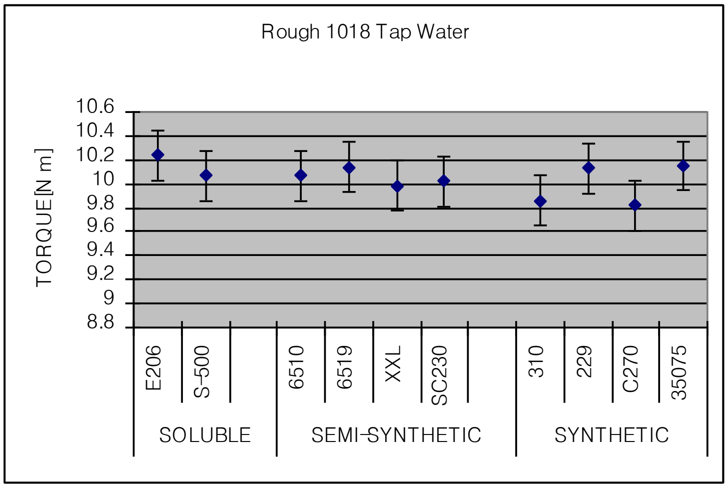

Figure 22. Rough 1018 Tap Water Drilling Experiment Torque Results

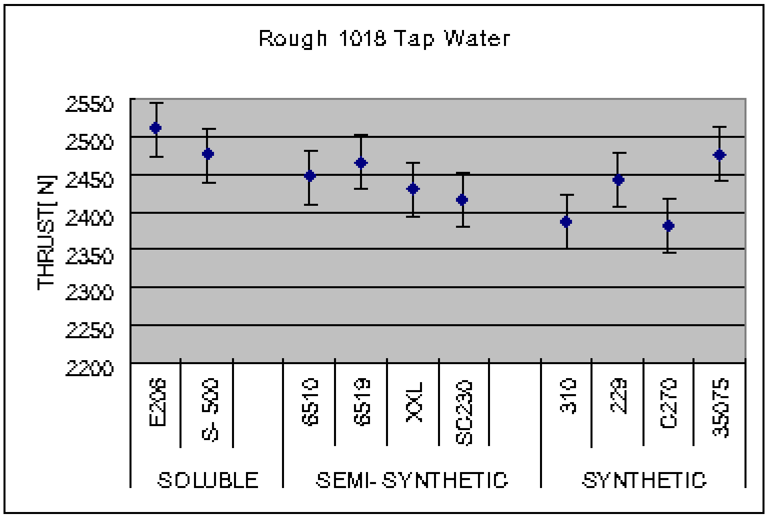

Figure 23. Rough 1018 Tap Water Drilling Experiment Thrust Results

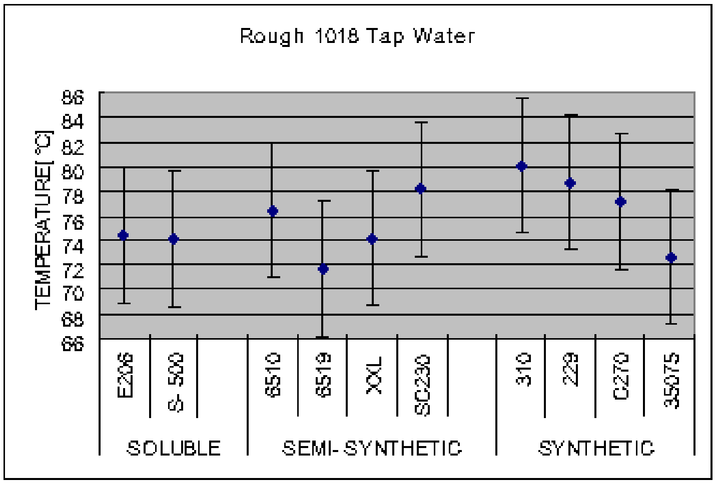

Figure 24. Rough 1018 Tap Water Drilling Experiment Temperature Results

Within MWF Type Conclusions for Rough 1018 Tap Water

The following conclusions were reached about individual fluids from comparisons within fluid types from the Rough 1018 Tap Water experiment:

- There was no difference between S-500 and E206 in torque, thrust, or temperature in the soluble oil MWF group.
- Of the semi-synthetic MWFs, XXL had a lower torque response than 6519.
- Of the semi-synthetic MWFs, SC230 had a lower thrust response than 6519.
- The semi-synthetic 6519 had a lower response to temperature than the semi-synthetic SC230.
- Of the synthetic MWFs, the torque and thrust responses of 310 and C270 were lower than 229 and 35075.
- Of the synthetic MWFs, 35075 had a statistically lower response to temperature than the other three synthetic MWFs.

Between MWF Type Conclusions for Rough 1018 Tap Water

When comparing between MWF types in the Rough 1018 Tap Water experiment, the conclusions were:

- The largest range of response for torque, thrust, and temperature was seen in the synthetic fluids. This could be due to the large variety of value additives that are included in synthetic fluids and the unknown impact they may have on cutting forces and temperature.
- The highest torque and thrust values were produced by the soluble oil E206.
- The temperature measurements had very large variances which affected the number of statistically different pairs.

Table 26. Summary of Results for Rough 1018 Tap Water Experiment

MWF		Soluble oil		Semi-synthetic				Synthetic			
		E206	S-500	6510	6519	XXL	SC230	310	229	C270	35075
Rough 1018 Tap Water	Torque	L	L	L	L	H	H	H	L	H	L
	Thrust	L	L	M	M	M	M	H	M	H	L
	Temperature	H	H	L	H	H	L	L	L	H	H

(L= Low, M= Medium, H= High)

The collective results of the Rough 1018 Tap Water experiment are presented in Table 26. This table provides a matrix of the fluids and their relative responses for each test response. Table 26 is read in the same way as described for Table 14 in Section 3.3.1.

3.4 Conclusions of Analysis Between Four Separate Experiments

The third type of analysis that was conducted for the experimental results was a comparison of the performance of individual fluids and fluid types between pairs of the four separate experiments. This allowed us to evaluate the effect that changing experimental conditions has on the performance of the fluids.

3.4.1. Effect of Workpiece Material on MWF Performance

The effect of workpiece material on the performance of the MWFs was examined by comparing the results of the Rough 1018 experiment with the results of the Rough 4340 experiment. The following observations were made:

- There was very little difference in the relative performance of the two soluble oil MWFs between the experiments. They both had statistically similar torque and thrust values. However, S-500 had a lower temperature response value in the Rough 4340 experiment.
- The MWF with the lowest response to torque and thrust in the Rough 4340 experiment was the synthetic 35075. However, 35075 had the highest torque and thrust values in Rough 1018 drilling experiment results. In addition, the synthetic fluid 310 provided the lowest response values of thrust and torque in the Rough 1018 experiment while it was the highest in thrust in the Rough 4340 experiment. From this, we concluded that the lubricant additives in 35075 and 310 reacted differently to the components in 4340 steel than in 1018 steel. This indicates that, unlike the tested soluble oil MWFs, the performance of some synthetic MWFs changes depending on the workpiece material used. These results are consistent with the work by Skells et al. [15] where drilling experiments were carried out on various materials, such as AISI 1045, AISI 4340, and AISI 303.
- A common result from the Rough 1018 and Rough 4340 experiments was that synthetic MWFs generally had lower torque and thrust values than soluble oil MWFs. This is consistent with previous findings by Leep [16] who concluded

that synthetic fluids perform better than soluble oils in drilling tests because synthetics clearly retarded drill edge wear when compared with the soluble oil.

3.4.2 Effect of Feedrate on MWF Performance

To examine the effect of feedrate on the performance of the MWFs, the results of the Rough 1018 experiment were compared to the results of the Finish 1018 experiment. The following observations were made:

- In general, the values of torque and thrust in the Finish 1018 drilling experiment were lower than those in the Rough 1018 experiment. This is expected because torque and thrust are functions of feedrate [17].
- The temperature values in the Finish 1018 experiment were significantly lower than those in the Rough 1018. This is also expected because of the lower feedrate.
- The range of temperature responses for the Rough 1018 experiment was more than twice as large as the range for the Finish 1018 experiment (11.36°C vs. 4.44°C). This suggests that there was less difference in MWF performance in terms of temperature at a lower feedrate than at a higher feedrate. This was confirmed by the results of the statistical analysis performed for both experiments. In the Finish 1018 experiment, only a single pair of the total 45 fluid pairs showed a statistical difference between mean temperatures. This can be compared to the 15 pairs that were statistically different with regards to temperature in the Rough 1018 experiment.
- The synthetic fluid Milacron 310 had lower torque and thrust responses in both the Rough 1018 experiment and the Finish 1018 experiment.

3.4.3 Effect of Dilutent on MWF Performance

To examine the effect of dilutent on the performance of the MWFs, the results of the Rough 1018 experiment were compared to the results of the Rough 1018 Tap Water experiment. The following observations were made:

- The overall torque and thrust results of the two experiments showed that the slightly harder water present in the Rough 1018 Tap Water experiment (75-85 ppm as $CaCO_3$) decreased cutting forces for most MWFs. This is similar to the results presented by Yang [13], who showed that a limited increase in water hardness can increase lubricity in some fluids.
- The torque and thrust results of Rough 1018 and Rough 1018 Tap Water showed the same relative performance of MWFs when compared to each other. The only fluid that showed a significant change relative to the others was the synthetic Milacron 310, which had far lower torque and thrust responses than all other fluids in the Rough 1018 experiment and had only a slightly lower torque and thrust response than most fluids in the Rough 1018 Tap Water experiment.
- There was a significant change in the temperature results between the two experiments. The use of tap water as the dilutent caused an increase in recorded temperature in several semi-synthetic (6510 and 6519) and synthetic fluids (310 and 229).

4. ADDITIONAL FLUID EVALUATION TESTS

The MWF evaluation drilling testbed and testing procedure, as outlined in Section 2 and employed in Section 3, looked only at three cutting force responses: torque, thrust, and temperature. One of the objectives of this project was to expand MWF evaluation through the measurement of additional fluid characteristics. In particular, viscosity, surface tension, emulsion stability, and corrosion inhibition were measured and analyzed. A list of all of the performance measurements and corresponding evaluation techniques are provided in Table 27.

4.1 Viscosity Test

Previous research by Bittorf et al. [18] found that viscosity can be an important property in regard to MWF performance. According to their conclusions, MWFs with higher viscosities perform better at lowering friction. The method of viscosity measurement used in this research project was ASTM method D2983 [19]. The DV-II+ PRO Digital Viscometer[7] used in this research, and located at the Illinois Sustainable Technology Center (formerly Illinois Waste Management and Research Center), is shown on the right in Fig. 25. This instrument measures the resistance of a fluid to the rotation of various shaped spindles at various rotational speeds and calculates the dynamic viscosity of the fluid based on the results. Because fluid temperature plays a very large role in fluid viscosity, a water bath circulator (Neslab RTE-111 Heated/Refrigerated Circulator[8]) was used to keep the fluids at a constant temperature during dynamic viscosity testing. The circulator can be seen in Fig. 25 on the left. All testing was carried out at 25°C. Fluids were tested at a 10% concentration with deionized water as the dilutent.

The results of dynamic viscosity testing for the ten MWFs studied in this report are shown in Table 28 and Fig. 26. Two replicates of each test were conducted and both are given in Table 28 along with the average of the two. Figure 26 shows the average viscosity value for each MWF along with error bars representing a 95% confidence interval calculated using pooled variance estimate and $\alpha = 0.05$. To provide a reference for the results of the dynamic viscosity testing, the dynamic viscosity of water is 0.8937 centipoise (cP) at 25℃.

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[7] www.brookfieldengineering.com
[8] www.aibltd.com

Table 27. MWF Evaluation Characteristics and Techniques

Evaluation Characteristic	Evaluation Technique
Lubrication	Drilling
Cooling	Drilling
Corrosion Resistance	ASTM Standard D4627-92
Emulsion Stability	Titration
Viscosity	Viscometer
Surface tension	Tensiometer

Table 28. Viscosity Test Results

Type	MWF	First Replicate	Second Replicate	Average
Soluble oil	E206	1.37	1.39	1.38cP
	S-500	1.44	1.47	1.46cP
Semi synthetic	6510	1.3	1.22	1.26cP
	6519	1.3	1.36	1.33cP
	XXI	1.3	1.32	1.31cP
	SC230	1.2	1.14	1.17cP
Synthetic	310	1.35	1.34	1.35cP
	229	1.27	1.32	1.23cP
	C270	1.11	1.13	1.12cP
	35075	1.32	1.24	1.28cP

Figure 25. Water Circulator and Brookfield Viscometer

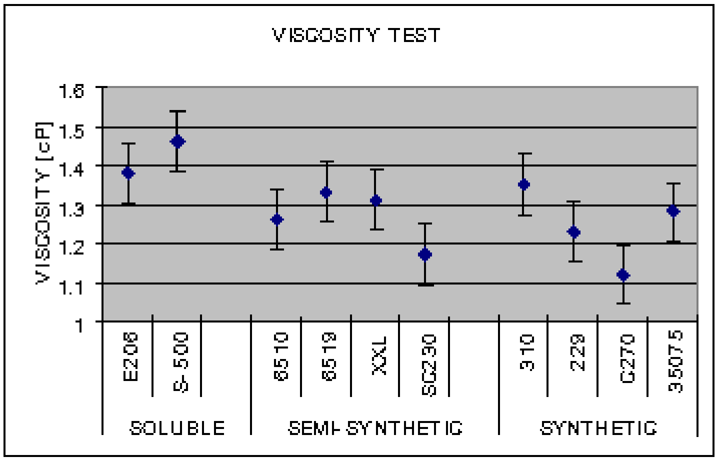

Figure 26. Viscosity Test Results

As shown in Table 28, soluble oil MWFs generally had higher viscosities than semi-synthetic and synthetic MWFs. This is reasonable because soluble oil MWFs contain a greater concentration of mineral oils. There was no significant difference between synthetic and semi-synthetic types in terms of viscosity although certain fluids within each type were more or less viscous than others.

4.2 Surface Tension Test

Surface tension is a measure of the inward pull of a liquid that tends to restrain the liquid from flowing or wetting a surface. It is related to such metalworking performance properties as cleaning action, lubrication, and foaming [1]. In this project, the Wilhelmy plate method was used to measure surface tension data for the ten MWFs. A Wilhelmy plate tensiometer uses a torsion arm balance with a platinum foil in a horizontal position hanging from the end of the arm. The test liquid is poured into a shallow cup and placed on an adjustable platform below the foil. The edge of the foil is submerged to just below the surface and the force required to pull the plate away from the surface provides the surface tension measurement. Using this procedure, pure water has a surface tension of 73 dyn/cm at 20℃. Addition of surface active agents such as emulsifiers, soaps and detergents like those found in MWFs will cause this value to decrease. The surface tension of a water-based metalworking fluid depends upon the type and concentration of surface-active agents present. Figure 27 shows the Wilhelmy plate tensiometer used in these tests.

Figure 27. Wilhelmy Plate Tensiometer

The results of the surface tension measurements are shown in Table 29 and Fig. 28. Each surface tension test result shown is the arithmetic mean of 5 replicates. Figure 28 includes error bars for each data point that extend for a 95% confidence interval calculated using pooled variance estimate and $\alpha = 0.05$. Unlike the viscosity results, no pattern emerged when comparing MWF types in Fig. 28. Most fluids had surface tension measurements between 27 and 32 dyn/cm. However, SC230 (semi-synthetic), 229 (synthetic), and C270 (synthetic) had values higher than 37 dyn/cm. This lack of a consistent pattern indicates that surface tension is more likely determined by emulsifiers and additives than the amount of oil present in the fluid. The largest range of values was seen in the synthetic fluids which could be due to the wide range of additives used in synthetic MWF composition.

Table 29. Surface Tension Test Results

Type	MWF	Average Result	Standard Deviation
Soluble oil	E206	31.3 dyn/cm	0.071
	S-500	29.44 dyn/cm	0.207
Semi synthetic	6510	28.18 dyn/cm	0.455
	6519	27.2 dyn/cm	0.000
	XXL	27.52 dyn/cm	0.311
	SC230	41.64 dyn/cm	0.152
Synthetic	310	28.84 dyn/cm	0.207
	229	37.38 dyn/cm	0.901
	C270	41.02 dyn/cm	0.130
	35075	31.28 dyn/cm	0.512

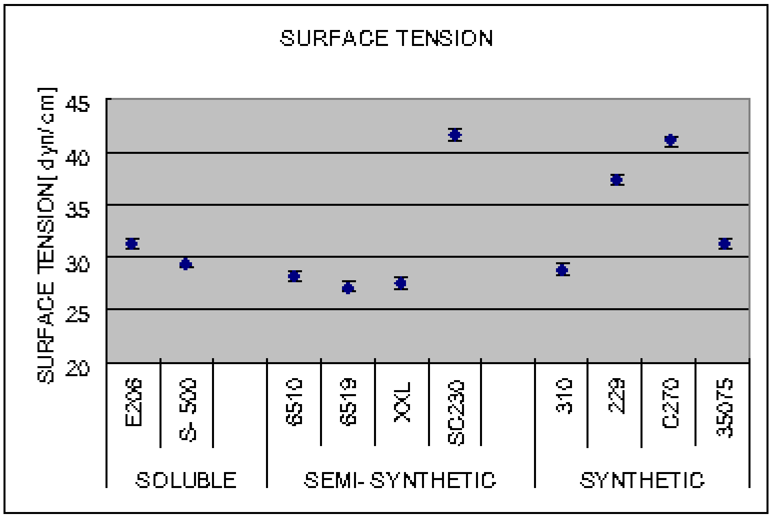

Figure 28. Surface Tension Test Results

4.3 Emulsion Stability Test

Soluble oil and semi-synthetic MWFs are made up of a dispersion of oil droplets in water, which is created through the use of surfactants and emulsifiers and relies upon electrostatic or steric repulsive barriers in order to maintain stability [1]. Synthetic MWFs, which by definition contain no oil, are actually microfine emulsions of soluble synthetic organic surfactants and lubricants. It is important to evaluate the emulsion stability of MWFs to determine how they will work in hard water situations.

Dilution emulsion stability depends upon both the quality of the MWF concentrate and the quality of the water used for dilution [1]. Levels of dissolved calcium and magnesium salts are referred to as “hardness,” usually expressed as ppm of calcium carbonate ($CaCO_3$). In addition to the initial water quality, consideration must be given to the unavoidable buildup of salts as the fluid is used and water evaporates [1]. Typically, a product is expected to perform under a variety of water conditions, from soft (75 ppm $CaCO_3$ or less) to very hard water (400 to 600 ppm $CaCO_3$) [1]. Water hardness (the calcium and magnesium ion content) is typically thought to be the component that deactivates anionic emulsifiers, rendering them insoluble in water and destabilizing the emulsion.

4.3.1 Emulsion Stability Test Procedure

The stability of each MWF was measured through calcium titration. In this test, the MWFs were diluted in deionized water containing various levels of calcium introduced as calcium chloride dehydrate under stirred conditions at a 10% MWF concentration. Mixing was accomplished by stirring for a period of 5 minutes. The diluted MWF solutions were transferred to beakers and allowed to settle for 24 hours. The fluid was then examined for the presence of either a cream layer or an oil phase. If a cream layer or an oil phase was detected in the fluid, a new test was conducted in which the fluid is mixed with deionized water containing the next lowest level of calcium [21]. By repeating this process, the range of calcium ions acceptable prior to destabilization for each MWF was discovered. For example, if a fluid mixed with deionized water containing 300 ppm calcium showed a cream layer or an oil phase, the next step was mixing the fluid with deionized water containing 200 ppm calcium. Figure 29 shows an emulsion stability test after 24 hours.

Figure 29. Emulsion Stability Test

4.3.2 Emulsion Stability Test Results

The emulsion stability test results are shown in Table 30 and Fig. 30 where "Low" and "High" mean that the MWF remains stable after being mixed with deionized water containing the "Low" level of calcium and becomes unstable after being mixed with deionized water containing the "High" level of calcium. In general, it took significantly more calcium ions to destabilize synthetic MWFs than semi-synthetic and soluble oil MWFs. However, the synthetic fluid C270 provided the exception by forming a film layer after just 280 ppm of calcium. Semi-synthetics behaved better than soluble oils in terms of emulsion stability, which indicates that the amount of oil in a fluid can play an important role in emulsion stability. Based on the results, soluble oil MWFs will have a much shorter life when used in hard water circumstances due to their lesser ability to maintain emulsion stability in the presence of hard water ions. Out of all the fluids tested, the synthetic MWF 35075 showed the most resistance to fluid breakdown. Castrol 6510, a semi-synthetic, is advertised as having good hard water stability and Table 30 supports this claim with 6510 outperforming the other semi-synthetic fluids.

Table 30. Emulsion Stability Test Results

Type	MWF	The range of Calcium ppm	
		Low	High
Soluble oil	S-500	0ppm	0ppm
	E206	120ppm	140ppm
Semi-synthetic	6519	200ppm	220ppm
	SC230	340ppm	360ppm
	6510	680ppm	700ppm
	XXL	420ppm	440ppm
Synthetic	C270	280ppm	300ppm
	310	1420ppm	1440ppm
	229	1180ppm	1200ppm
	35075	2300ppm	2320ppm

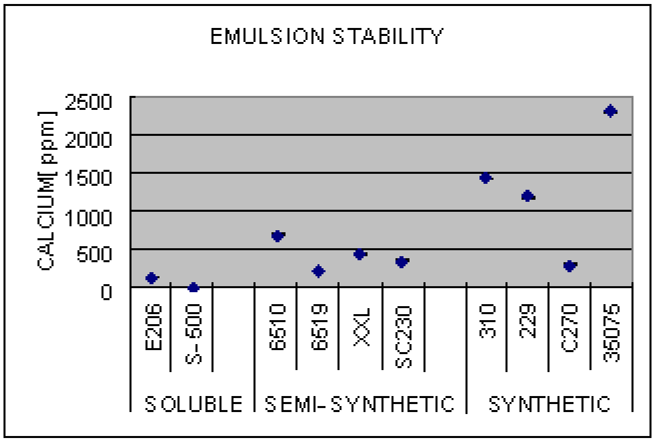

Figure 30. Emulsion Stability Test Results

4.4 Corrosion Inhibition Test

Aqueous-based MWFs may either be solubilized or emulsified in water, with the water making up approximately 90 to 98% of the total volume. However, water has a great capacity to corrode ferrous metals. Thus, it is extremely important for an aqueous-based MWF to have the ability to prevent corrosion when used around corrodible materials.

4.4.1 Corrosion Inhibition Test Procedure

The ASTM standard D4627-92 [20] was used as the corrosion inhibition test procedure. The standard is based on an assumed relationship between the results of this test and a similar ability of the subject MWF to prevent rust on nested parts or in drilled holes containing chips, etc. However, it must be understood that controlled laboratory conditions, metal types, etc., do not always correlate to those on the shop floor.

The corrosion inhibition test was conducted by preparing 50mL of MWF at each desired concentration in 100mg/L hardness water. A filter paper was placed in a dry Petri dish and 5.0mL of diluted MWF was used to wet the paper. Following this, 4.0g of gray cast iron chips were evenly distributed in the dish and allowed to sit for 24 hours. After 24 hours, the filter paper was examined to see whether it is stained by rusting chips. The "breakpoint" is defined as the weakest concentration tested that left no rust stain on the filter paper. This value is used to compare the rust inhibiting properties of various fluids. A high concentration breakpoint indicates a low ability to inhibit corrosion.

4.4.2 Corrosion Inhibition Test Results

The results of the corrosion inhibition test are shown in Table 31 and Fig. 31. These results are a useful guideline to determine the ability of water-diluted MWFs to prevent or minimize rust under specific conditions. These results may be more or less important to a given machining operation depending on whether the workpiece material is ferrous.

As shown in Table 31, within each fluid type there was a similar range in breakthrough values. Therefore, no pattern emerged that provides correlation between fluid type and corrosion inhibition. This indicates that the ability to prevent the corrosion of ferrous metals is determined by additives rather than the amount of oil. S-500 and SC230 are the MWFs with the least amount of corrosion inhibition among those tested. The gray cast iron chips rusted even at 10% concentration for these fluids. Synthetic MWFs 310 and 229 allowed rust to form at 7%. All of the other MWFs did not show rust until the concentration dropped to 2.5% or lower.

Table 31. Corrosion Inhibition Test Results

Type	MWF	Breakpoint
Soluble oil	E206	2.50%
	S-500	10%
Semi synthetic	6510	2%
	6519	1.50%
	XXI	2.50%
	SC230	10%
Synthetic	310	7%
	229	7%
	C270	2%
	35075	1.50%

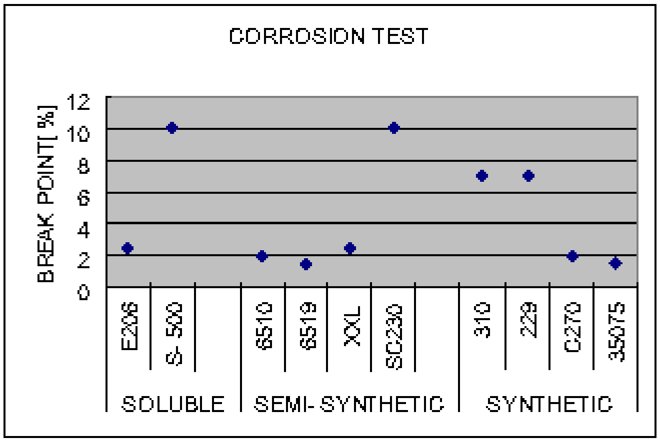

Figure 31. Corrosion Inhibition Test Results

4.5 Summary

In this section, additional MWF evaluation tests were conducted and the test results were described. The following conclusions were reached:

1. Based on viscosity testing, soluble oil MWFs in general have a higher viscosity, which indicates that the concentration of oil plays a role in viscosity.
2. Surface tension is more likely determined by emulsifiers and additives than the concentration of oil.
3. Semi-synthetics showed more resistance to fluid breakdown in terms of emulsion stability than soluble oils, which is likely due to the emulsifiers used and smaller micro-emulsion size of the semi-synthetics.
4. The ability to prevent the corrosion of ferrous metals was found to be influenced by additives rather than the amount of oil in the fluid.

The responses for the additional tests have been compiled in Table 32. In this table, the measured values are labeled as Low, Medium, or High. In viscosity and surface tension, a relatively large value, for example 1.46 cP for viscosity for S-500, would be listed as a "High" value. A relatively low value, for example 27.52 dyn/cm for surface tension for XXL, would be listed as a "Low" value. The meanings of High, Medium, and Low change for the emulsion stability and corrosion inhibition responses. For these tests, "High" means better performing in stability or corrosion inhibition. The delineation of Low, Medium, and High was determined using a 3-4-3 approach in which the top three fluids were marked "High", the next four marked "Medium" and the last three were marked "Low." The exception to this 3-4-3 approach was corrosion inhibition where there were three clear groupings that were used for delineation.

Table 32. Summary of Additional Test Results

MWF		**Soluble oil**		**Semi-synthetic**				**Synthetic**			
		E206	**S-500**	**6510**	**6519**	**XXL**	**SC230**	**310**	**229**	**C270**	**35075**
Additional Tests	**Viscosity**	H	H	M	M	M	L	H	L	L	M
	Surface Tension	M	M	L	L	L	H	M	H	H	M
	Emulsion Stability	L	L	M	L	M	M	H	H	M	H
	Corrosion Inhibition	H	L	H	H	H	L	M	M	H	H

(L= Low, M= Medium, H= High)

5. CONCLUSIONS

The following conclusions were reached based on the research done for this project:

1. The second generation drilling testbed and accompanying procedure was found to be very repeatable and sensitive enough to be useful for discriminating the performance of MWFs in lubrication and cooling by measuring torque, thrust, and temperature values.
2. The high level of repeatability within experiments was confirmed through the low coefficients of variation in drilling experiments. The largest coefficient of variation found through four separate drilling experiments for cutting forces was 0.037 and for temperature was 0.092.
3. It was determined that the lubricant additives of certain synthetic fluids react differently to workpiece material composition. This was evident when changing workpiece material from AISI 1018 steel to AISI 4340 steel.
4. Under most experimental conditions, the synthetic fluids had lower torque and thrust responses than the soluble oil fluids.
5. It was determined that, as the feedrate is lowered and the cutting condition becomes less extreme, the difference between the cooling ability of most MWFs is lowered. The same was not necessarily true of cutting forces, with differences still being recognized between fluids in torque and thrust.
6. It was found that using a dilutent of tap water with water hardness of 75-85 ppm (as $CaCO_3$) versus deionized water led to a slight decrease in torque and thrust response for most fluids and led to an increase in temperature response for several metalworking fluids.
7. Based on viscosity testing, soluble oil MWFs in general were found to have a higher viscosity, which indicates that the concentration of oil plays a role in viscosity.
8. Surface tension is more likely determined by emulsifiers and additives than the concentration of oil.
9. Similar to the viscosity result, semi-synthetics showed more resistance to fluid breakdown in terms of emulsion stability than soluble oils, which is likely due to the emulsifiers used and smaller micro-emulsion size of the semi-synthetics.
10. The prevention of corrosion of ferrous metals was found to be influenced by additives rather than the amount of oil in the fluid.

All of the experimental results collected in the conduct of this research are shown in Table 33. This table provides a matrix of the fluids and their relative responses for each test response. Results in Table 33 are delineated as High, Medium, or Low. For all of the drilling experiment results, as well as the corrosion inhibition and emulsion stability tests, a labeling as “High” means relatively good performance. For example, a fluid with a low thrust response relative to the other fluids would garner a “High” label in the appropriate box in Table 33. In the drilling experiment portion of the matrix, the fluids marked “High” had average values that fell within the 95% confidence interval of the fluid with the lowest response value. This method is the same for all three test responses: torque, thrust, and temperature. Likewise, fluids marked “Low” had average values that fell within the 95% confidence interval of the highest response value for the three test responses. All fluids not falling into either the “High” or the “Low” categories were marked as “Medium”.

The responses for the additional tests (viscosity, surface tension, emulsion stability, and corrosion inhibition) did not use the 95% confidence interval approach because the much lower variation within test responses did not make it practical. Rather, a 3-4-3 approach was used in which the top three fluids were marked “High”, the next four marked “Medium” and the last three were marked “Low.” For the emulsion stability and corrosion inhibition tests, “High” means better performing in stability or corrosion inhibition. For the viscosity and surface tension tests, the idea of what is “better” is not satisfactorily known. Therefore, “High” means the three fluids with the highest viscosity values and highest surface tension values. Relative price is listed in the same 3-4-3 format with the most costly fluids garnering a “High” level.

When using this table, it is important to remember that these values are, strictly speaking, only applicable for the experimental conditions outlined in this report. However, the relative performances of the fluids should prove useful to end-users in determining the fluid that will best serve a given machining situation.

Table 33. Collected MWF Experiment Results

MWF		Soluble oil		Semi-synthetic				Synthetic			
		E206	S-500	6510	6519	XXL	SC230	310	229	C270	35075
Rough 1018	**Torque**	L	L	M	M	M	M	H	L	M	L
	Thrust	L	M	M	M	M	M	H	M	M	L
	Temperature	H	H	H	H	L	L	L	M	L	H
Rough 4340	**Torque**	L	L	L	L	H	L	H	L	M	H
	Thrust	L	L	L	L	L	L	M	H	H	H
	Temperature	M	M	H	H	H	H	M	M	L	L
Finish 1018	**Torque**	M	M	M	M	H	M	H	L	H	M
	Thrust	L	L	M	L	M	L	H	L	M	M
	Temperature	L	L	L	H	L	L	L	L	L	L
Rough 1018 Tap Water	**Torque**	L	L	L	L	H	H	H	L	H	L
	Thrust	L	L	M	M	M	M	H	M	H	L
	Temperature	H	H	L	H	H	L	L	L	H	H
Additional Tests	**Viscosity**	H	H	M	M	M	L	H	L	L	M
	Surface Tension	M	M	L	L	L	H	M	H	H	M
	Emulsion Stability	L	L	M	L	M	M	H	H	M	H
	Corrosion Inhibition	H	L	H	H	H	L	M	M	H	H
Relative Price		M	M	L	L	M	L	M	M	L	H

(L= Low, M= Medium, H= High)

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APPENDIX A – Drilling Experiments Raw Data

Table A-1. Rough 1018 Drilling Experiment

Type	Fluid	Torque	Thrust	Temperature
Soluble oil	1-E206	1079.00	2616.00	60.50
	2-E206	1065.00	2604.00	67.80
	3-E206	1110.00	2682.00	73.40
	4-E206	1084.00	2631.00	74.70
	5-E206	1083.00	2597.00	70.30
	Average	1084.20	2626.00	69.34
	Standard deviation	16.30	33.86	5.63
	1-S-500	1035.00	2525.00	74.40
	2-S-500	1045.00	2542.00	73.90
	3-S-500	1045.00	2585.00	69.80
	4-S-500	1079.00	2583.00	69.30
	5-S-500	1076.00	2606.00	72.50
	Average	1056.00	2568.20	71.98
	Standard deviation	20.07	33.48	2.33
Semi-synthetic	1-6510	1031.00	2490.00	63.30
	2-6510	1047.00	2558.00	66.40
	3-6510	1017.00	2546.00	69.50
	4-6510	1057.00	2570.00	67.20
	5-6510	1074.00	2606.00	72.90
	Average	1045.20	2554.00	67.86
	Standard deviation	22.19	42.24	3.59
	1-6519	1031.00	2516.00	62.40
	2-6519	1070.00	2562.00	66.70
	3-6519	1072.00	2651.00	71.60
	4-6519	1035.00	2575.00	66.30
	5-6519	1036.00	2565.00	67.90
	Average	1048.80	2573.80	66.98
	Standard deviation	20.36	48.78	3.31
	1-XXL	1023.00	2478.00	69.10
	2-XXL	1027.00	2487.00	70.40
	3-XXL	1036.00	2586.00	78.20
	4-XXL	1015.00	2534.00	80.90
	5-XXL	1079.00	2570.00	69.50
	Average	1036.00	2531.00	73.62
	Standard deviation	25.20	48.22	5.52
	1-SC230	1040.00	2529.00	82.40
	2-SC230	1043.00	2531.00	74.00
	3-SC230	1012.00	2494.00	78.00
	4-SC230	1015.00	2521.00	80.10
	5-SC230	1012.00	2479.00	70.80
	Average	1024.40	2510.80	77.06
	Standard deviation	15.69	23.11	4.67
Synthetic	1-310	970.00	2400.00	74.70
	2-310	979.00	2418.00	70.00
	3-310	950.00	2355.00	68.50
	4-310	1024.00	2533.00	80.00
	5-310	1002.00	2419.00	77.20
	Average	985.00	2425.00	74.08
	Standard deviation	28.71	65.72	4.82
	1-229	1101.00	2513.00	74.00
	2-229	1085.00	2512.00	72.40
	3-229	1017.00	2485.00	70.20
	4-229	1053.00	2507.00	74.60
	5-229	1053.00	2510.00	71.20
	Average	1061.80	2505.40	72.48
	Standard deviation	32.55	11.63	1.85
	1-C270	1017.00	2490.00	79.60
	2-C270	1050.00	2534.00	77.70
	3-C270	1054.00	2493.00	77.00
	4-C270	1055.00	2476.00	78.70
	5-C270	1032.00	2535.00	78.70
	Average	1041.60	2505.60	78.34
	Standard deviation	16.59	27.15	1.01
	1-35075	1090.00	2593.00	76.90
	2-35075	1070.00	2571.00	76.20
	3-35075	1050.00	2588.00	63.40
	4-35075	1082.00	2567.00	64.30
	5-35075	1100.00	2582.00	73.10
	Average	1078.40	2580.20	70.78
	Standard deviation	19.31	11.03	6.49

Table A-2. Rough 4340 Drilling Experiment

Type	Fluid	Torque	Thrust	Temperature
Soluble oil	1-E206	1088	2541	71.94
	2-E206	1089	2536	72.54
	3-E206	1084	2489	70.44
	4-E206	1098	2581	70.04
	5-E206	1094	2572	70.34
	Average	1090.6	2543.8	71.06
	Standard deviation	5.4589376	36.231202	1.1077003
	1-S-500	1091	2539	74.64
	2-S-500	1089	2523	73.54
	3-S-500	1086	2554	72.14
	4-S-500	1085	2497	73.74
	5-S-500	1085	2532	74.44
	Average	1087.2	2529	73.7
	Standard deviation	2.6832816	21.177819	0.9864076
Semi-Synthetic	1-6510	1089	2549	68.84
	2-6510	1084	2549	69.84
	3-6510	1091	2540	67.34
	4-6510	1085	2540	67.24
	5-6510	1087	2523	67.94
	Average	1087.2	2540.2	68.24
	Standard deviation	2.8635642	10.616026	1.0977249
	1-6519	1081	2538	64.54
	2-6519	1087	2527	67.84
	3-6519	1086	2561	68.64
	4-6519	1095	2566	69.24
	5-6519	1089	2570	69.94
	Average	1087.6	2552.4	68.04
	Standard deviation	5.07937	18.849403	2.1035684
	1-XXL	1084	2568	69.34
	2-XXL	1077	2562	70.34
	3-XXL	1074	2561	67.74
	4-XXL	1077	2582	68.04
	5-XXL	1070	2524	66.54
	Average	1076.4	2559.4	68.4
	Standard deviation	5.1283526	21.489532	1.472413
	1-SC230	1095	2568	70.24
	2-SC230	1086	2541	67.14
	3-SC230	1089	2563	68.84
	4-SC230	1087	2553	70.04
	5-SC230	1090	2591	69.64
	Average	1089.4	2563.2	69.18
	Standard deviation	3.5071356	18.660118	1.2601587
Synthetic	1-310	1046	2443	70.14
	2-310	1069	2509	76.94
	3-310	1074	2547	72.74
	4-310	1078	2538	71.24
	5-310	1079	2541	73.04
	Average	1069.2	2515.6	72.82
	Standard deviation	13.553597	43.148581	2.5839892
	1-229	1074	2368	72.04
	2-229	1089	2467	76.14
	3-229	1107	2481	74.94
	4-229	1109	2523	72.24
	5-229	1100	2530	72.64
	Average	1095.8	2473.8	73.6
	Standard deviation	14.481022	64.943822	1.8338484
	1-C270	1065	2471	74.74
	2-C270	1094	2521	74.84
	3-C270	1085	2486	74.94
	4-C270	1081	2501	72.94
	5-C270	1087	2528	74.34
	Average	1082.4	2501.4	74.36
	Standard deviation	10.807405	23.733942	0.8258329
	1-35075	1053	2441	73.44
	2-35075	1061	2451	78.14
	3-35075	1066	2454	75.24
	4-35075	1077	2487	76.84
	5-35075	1078	2497	76.24
	Average	1067	2466	75.98
	Standard deviation	10.653638	24.474477	1.7657859

Table A-3. Finish 1018 Drilling Experiment

Type	Fluid	Torque	Thrust	Temperature
Soluble oil	1-E206	724.00	1743.00	65.04
	2-E206	726.00	1731.00	69.54
	3-E206	733.00	1751.00	63.04
	4-E206	735.00	1757.00	69.44
	5-E206	730.00	1727.00	71.14
	Average	729.60	1741.80	67.64
	Standard deviation	4.62	12.77	3.43
	1-S-500	728.00	1742.00	66.62
	2-S-500	715.00	1683.00	68.72
	3-S-500	726.00	1765.00	66.62
	4-S-500	718.00	1748.00	69.32
	5-S-500	724.00	1732.00	73.72
	Average	722.20	1734.00	69.00
	Standard deviation	5.50	30.93	2.91
Semi-synthetic	1-6510	741.00	1694.00	63.12
	2-6510	725.00	1692.00	66.92
	3-6510	719.00	1718.00	66.02
	4-6510	722.00	1678.00	71.02
	5-6510	718.00	1697.00	71.12
	Average	725.00	1695.80	67.64
	Standard deviation	9.35	14.39	3.43
	1-6519	705.00	1689.00	59.82
	2-6519	732.00	1743.00	63.22
	3-6519	753.00	1664.00	66.62
	4-6519	725.00	1697.00	66.52
	5-6519	718.00	1724.00	66.62
	Average	726.60	1703.40	64.56
	Standard deviation	17.81	30.79	3.02
	1-XXL	698.00	1656.00	72.62
	2-XXL	709.00	1709.00	63.62
	3-XXL	716.00	1729.00	63.62
	4-XXL	701.00	1631.00	66.62
	5-XXL	703.00	1680.00	69.92
	Average	705.40	1681.00	67.28
	Standard deviation	7.16	39.41	3.96
	1-SC230	716.00	1707.00	65.12
	2-SC230	723.00	1723.00	69.42
	3-SC230	724.00	1712.00	63.72
	4-SC230	727.00	1726.00	63.12
	5-SC230	729.00	1698.00	67.22
	Average	723.80	1713.20	65.72
	Standard deviation	4.97	11.52	2.60
Synthetic	1-310	713.00	1612.00	66.62
	2-310	706.00	1695.00	66.52
	3-310	708.00	1640.00	68.72
	4-310	708.00	1619.00	67.32
	5-310	701.00	1620.00	62.72
	Average	707.20	1637.20	66.38
	Standard deviation	4.32	33.95	2.23
	1-229	742.00	1688.00	63.52
	2-229	749.00	1690.00	71.82
	3-229	740.00	1734.00	66.82
	4-229	756.00	1690.00	68.12
	5-229	747.00	1720.00	69.82
	Average	746.80	1704.40	68.02
	Standard deviation	6.30	21.23	3.14
	1-C270	689.00	1582.00	67.32
	2-C270	718.00	1705.00	63.72
	3-C270	709.00	1739.00	66.32
	4-C270	708.00	1684.00	67.62
	5-C270	733.00	1723.00	63.62
	Average	711.40	1686.60	65.72
	Standard deviation	16.04	61.96	1.93
	1-35075	721.00	1698.00	66.92
	2-35075	720.00	1706.00	68.82
	3-35075	721.00	1716.00	66.62
	4-35075	732.00	1665.00	63.62
	5-35075	719.00	1667.00	66.12
	Average	722.60	1690.40	66.42
	Standard deviation	5.32	23.18	1.87

Table A-4. Rough 1018 Tap Water Drilling Experiment

Type	Fluid	Torque	Thrust	Temperature
Soluble oil oil	1-E206	1037.30	2497.80	83.92
	2-E206	1022.00	2493.30	76.12
	3-E206	1016.60	2517.80	70.65
	4-E206	1014.60	2527.40	69.60
	5-E206	1030.70	2512.00	71.75
	Average	1024.24	2509.66	74.41
	Standard deviation	9.60	14.10	5.87
	1-S-500	1030.40	2474.30	74.07
	2-S-500	994.19	2446.80	75.41
	3-S-500	1000.00	2464.60	75.33
	4-S-500	1026.00	2528.60	72.31
	5-S-500	985.94	2464.10	73.48
	Average	1007.31	2475.68	74.12
	Standard deviation	19.78	31.20	1.31
Semi-synthetic	1-6510	1024.20	2485.60	81.73
	2-6510	1024.90	2455.60	78.51
	3-6510	1005.50	2451.60	75.02
	4-6510	987.89	2402.80	71.74
	5-6510	994.74	2438.20	75.23
	Average	1007.45	2446.76	76.44
	Standard deviation	16.83	30.07	3.80
	1-6519	1014.40	2424.50	64.05
	2-6519	1030.70	2503.90	74.73
	3-6519	1015.40	2473.80	75.77
	4-6519	1001.60	2473.30	73.52
	5-6519	1008.60	2457.80	70.40
	Average	1014.14	2466.66	71.69
	Standard deviation	10.77	28.89	4.72
	1-XXL	1017.50	2460.30	76.91
	2-XXL	983.29	2402.50	77.12
	3-XXL	1011.40	2465.10	74.57
	4-XXL	992.02	2393.30	71.88
	5-XXL	984.76	2433.60	70.31
	Average	997.79	2430.96	74.16
	Standard deviation	15.71	32.64	3.02
	1-SC230	1038.60	2448.30	83.68
	2-SC230	1013.60	2426.40	81.31
	3-SC230	982.97	2386.10	75.29
	4-SC230	984.04	2412.30	75.23
	5-SC230	988.98	2408.30	75.19
	Average	1001.64	2416.28	78.14
	Standard deviation	24.12	23.01	4.07
Synthetic	1-310	1008.40	2360.80	89.42
	2-310	1005.00	2376.60	83.87
	3-310	966.72	2386.30	76.54
	4-310	976.80	2431.80	77.31
	5-310	975.48	2378.40	73.09
	Average	986.48	2386.78	80.05
	Standard deviation	18.90	26.81	6.53
	1-229	1020.20	2450.00	78.90
	2-229	1010.90	2434.40	86.60
	3-229	1010.70	2444.50	75.95
	4-229	998.03	2413.70	77.71
	5-229	1025.70	2470.50	74.29
	Average	1013.11	2442.62	78.69
	Standard deviation	10.57	20.85	4.76
	1-C270	1005.00	2394.10	78.31
	2-C270	976.22	2375.80	81.35
	3-C270	973.00	2343.80	75.16
	4-C270	979.13	2419.10	75.40
	5-C270	975.09	2375.10	75.46
	Average	981.69	2381.58	77.14
	Standard deviation	13.22	27.69	2.69
	1-35075	1028.00	2494.00	74.81
	2-35075	1035.60	2467.00	76.49
	3-35075	990.42	2437.00	74.88
	4-35075	1014.40	2532.40	67.13
	5-35075	1005.40	2455.00	70.12
	Average	1014.76	2477.08	72.69
	Standard deviation	17.96	37.22	3.91