VOL. 59, NO. 3

March 2003

Lubrication Engineering

JOURNAL OF THE SOCIETY OF TRIBOLOGISTS AND LUBRICATION ENGINEERS

Heat Exchange Coefficient in Thermoelastic Contact

Evaluating Metalworking Fluids Tapping Torque Test

Lubrication Fundamentals:
Metalworking Fluids

2003 STLE Annual Meeting:
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Experimental and Statistical Design Considerations for Economical Evaluation of Metalworking Fluids Using the Tapping Torque Test©

Recently, multiple evaluation systems (MES) that allow for a large number of tapping torque tests (T^3) to be performed on a single workpiece have been gaining in popularity for the evaluation of metalworking fluids (MWFs). However, MWF formulators have had difficulty obtaining statistically significant results or results consistent with experience in the field, raising questions about the efficacy of MES. This paper develops statistical and experimental design considerations for MWF evaluation by MES that aim to maximize the sensitivity of T^3 to MWF performance and to improve the correlation between laboratory and field performance. Toward this end, a metric of resolving power is developed that quantifies the ability of a T^3 operating condition (speed, material, tool size, etc.) to discriminate between MWFs. It is shown that as resolving power increases, the correlation of T^3 response to expected field performance increases. The paper concludes with a discussion regarding economic trade-offs between increased cost, resolving power, and statistical significance of T^3 results.

Final manuscript approved February 12, 2003
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NOMENCLATURE

CI	= confidence interval for a given cut, [N•cm]
N	= number of replicate cuts at a given test condition
n	= number of torque values recorded for a single cut
r	= number of fluids evaluated at a given test condition
S_x	= observed variance for a single cut, [N^2•cm^2]
$S_{\bar{x}}$	= observed variance for a given test condition, [N^2•cm^2]
s	= number of replicate cuts for a given fluid
t	= t-distribution ordinate
$\bar{X}$	= average torque value for the plateau region of a cut profile, [N•cm]
$\bar{\bar{X}}$	= average torque value for a given test condition, [N•cm]
$\bar{\bar{\bar{X}}}$	= average torque value of all fluids for a given test condition, [N•cm]
α	= percent confidence
η	= percent tapping torque efficiency
ρ	= correlation coefficient
$\hat{\sigma}_x$	= variance for a single cut, [N^2•cm^2]
$\hat{\sigma}_{\bar{x}}$	= estimated variance for a given test condition, [N^2•cm^2]
μ	= true torque value for a single cut, [N•cm]
$\bar{\mu}$	= estimated torque value for a given test condition, [N•cm]

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KEYWORDS

Metalworking Fluid Evaluation; Tapping; Machining; Economics; Tool Coatings; Applied Statistics

INTRODUCTION

The search for effective laboratory test methods for the evaluation of metalworking fluid (MWF) field performance has been in progress for over 50 years. Standard laboratory wear and extreme pressure tests, such as the pin and v-block evaluation (ASTM D 2670) and the Four Ball Wear (ASTM D 4172) tests, have gained limited use but have not been found to be adequate indicators of machining performance under manufacturing conditions *(1)-(3)*. In fact, much evidence exists in the literature to suggest that one can only reasonably predict the lubrication performance of MWFs in cutting operations through the use of a real machining operation such as reaming, drilling, or tapping *(1), (4)-(8)*. Naturally, the closer a test condition is to the actual manufacturing condition, the better its prediction. However at the early stages of formulation, effective laboratory tests are needed that streamline the development process. Of the many laboratory scale performance tests that have been developed toward this end, the tapping torque test (T^3) has been gaining wide acceptance because it fulfills a number of desired testing requirements: (a) correlation with field results, (b) simplicity, (c) speed, (d) economy, (e) small test samples, (f) precision, and (g) severe conditions *(9)*. In addition, it has been demonstrated that a correlation exists between low tapping torque, long tool life, good surface integrity of the thread, and an effective metalworking fluid *(2), (6), (10)*.

According to ASTM D 5619, the Standard for Comparing Metal Removal Fluids Using the Tapping Torque Test Machine *(11)*, "[the tapping torque test] method can be used to more accurately predict the lubricating properties of a metal removal fluid than previously available laboratory scale tests." It is important to note however that ASTM D 5619 does not specify default operating conditions including machining speeds, workpiece material, tool alloy, tool size, or tool coating. One can reasonably expect that a lack of accounting for such controllable variables, as well as uncontrolled variables such as workpiece hardness and tool wear, have led to the wide variation in T^3 results reported in the literature *(1), (2), (9), (11), (12)*. Consistent with these observations, MWF formulators have expressed difficulties obtaining statistically significant results or results consistent with expected outcomes based on experience. This has raised questions about the efficacy of T^3 for the evaluation of MWFs.

This paper investigates experimental design approaches that explicitly minimize sources of variability in T^3 and recommends an experimental design paradigm that can enhance the power of tapping torque experiments for evaluating MWF performance. Specifically this paper: (a) proposes a method to design, conduct, and interpret MWF evaluation experiments using newly available tapping torque testbeds, (b) demonstrates that the selection of operating and machining conditions is critical to the ability to distinguish MWF performance and predict field performance using tapping torque tests, and (c) establishes the trade-offs between cost and sensitivity when designing a T^3 experiment.

SINGLE EVALUATION SYSTEMS (SES) *VS.* MULTIPLE EVALUATION SYSTEMS (MES)

ASTM D 5619 was designed for T^3 systems that conduct a single tapping evaluation (SES) per workpiece. Performing each test evaluation on a new workpiece introduces significant uncertainty into the evaluation process since workpiece to workpiece variation can overshadow differences in torque responses caused by MWFs. To counteract this, SES operators try to obtain workpieces produced by the same manufacturer in the same batch, sometimes at a significant cost.

Difficulties with workpiece variation and per-test cost have led to the development of tapping torque testbeds which allow multiple test conditions to be evaluated on a single workpiece (MES). While this makes T^3 potentially more convenient and cost effective by reducing variability associated with workpiece material, this type of system introduces new challenges in experimental design and interpretation given the potential for tool wear and localized workpiece hardness within a single workpiece. Since ASTM D 5619 was not designed for MES, additional considerations are discussed below that assist in capitalizing upon the unique opportunities afforded by multiple evaluations on a single workpiece.

MEASURING VARIABILITY AND CONFIDENCE IN T^3

A tapping apparatus typically reports torque values that are measured as a function of depth, yielding a cutting torque profile as shown in Fig. 1(a). The distribution of torque values in the plateau region of the profile, presumably without systematic or obvious sources of variation such as entry and exit forces or chip clogs, should follow a normal distribution as expected by the central limit theorem (Fig. 1(b)). The average of the cutting torque values in the plateau region ($\bar{X}$) serves as an estimate of the desired "true" tapping torque for the selected operating condition (μ). Recognizing that since there exists a relatively low number of points in the plateau region, the normal distribution is approximated by the t-distribution, and a confidence interval with certainty level α for μ is expressed by *(13)*,

$$\text{Confidence Interval, } CI = \bar{X} \pm r_{\alpha,n-1} \times \frac{S_x}{\sqrt{n}} \qquad [1]$$

where n is the number of cutting torque values in the plateau, $t_{\alpha,n\text{-}1}$ is the t-distribution ordinate corresponding to the α level of confidence given n-1 degrees of freedom, and S_x is the estimated standard deviation about $\bar{X}$. Equation [1] represents a quantified expression of the degree of certainty that can be associated with the estimate of μ by $\bar{X}$ observed experimentally.

Within an individual test, n is limited by depth and instrumentation resolution, and since S_x is typically large, it

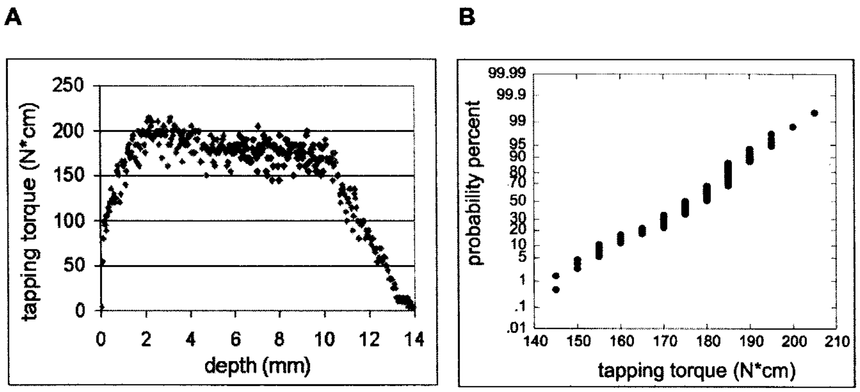

Fig. 1—(a) A typical cutting profile with the plateau region indicated (bolded dots) and (b) a normal probability plot of the tapping torque values in the plateau region. Although the testbed applied in this research can only resolve tapping torque to a resolution of 5 N*cm, the close fit (R^2=0.98) of (b) to linearity indicates the plateau region outcomes can be reasonably represented by a normal distribution.

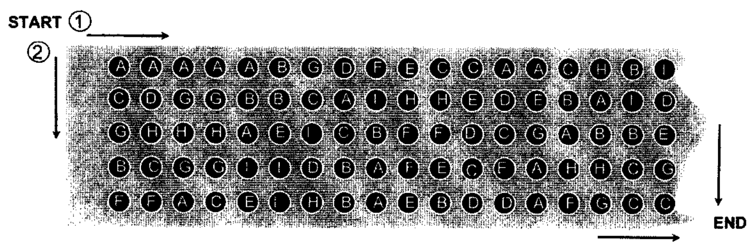

Fig. 2—Sample randomization of T^3 conditions on a workpiece, where the letter indicates a test condition for evaluation (tool/fluid combination) and the arrows indicate the order of evaluation (left to right across a row; then top to bottom down the workpiece). "A" represents the reference test condition used for tool break-in and efficiency calculations. By comparing "A" tests near the beginning with "A" tests near the end, it is possible to observe if tool wear has likely had an influence on the experiments.

follows that the confidence region determined by Eq. [1] is typically too large to distinguish differences between MWF formulations. For this reason, many replicate tests (N) for a given operating condition are performed in MES. Over multiple tests, the best single point estimate for the true tapping torque (μ) is $\overline{\overline{X}}$, which is the average of all the plateau values observed over multiple tests at the operating condition under consideration. The confidence interval for $\overline{\overline{X}}$ is described by,

$$\text{Confidence Interval, CI} = \overline{\overline{X}} \pm t_{\alpha,N-1} \times \frac{S_{\bar{x}}}{\sqrt{N}} \qquad [2]$$

Equation [2] captures the fundamental trade-off in designing T^3 experiments: the higher the uncertainty inherent to the experimental design ($S_{\bar{x}}$), the more tests that have to be performed (N) to decrease the confidence interval enough to be sensitive to differences in MWF formulation performance. In other words, while replicate testing increases evaluation time and cost, it increases sensitivity to MWF differences, which is desired during the laboratory evaluation of MWF performance.

Experimental replication also helps to spread out uncontrollable sources of variation (e.g., localized workpiece hardness and tool wear) equally for all MWF evaluations as long as the experiments are performed in a randomized order. Randomization attempts to distribute unknown and unknowable sources of variability evenly over the experimental design, reducing the impact of local effects and thus reducing the vulnerability of the experiment to misleading conclusions influenced by an unknown random factor. A sample randomization pattern for MES is provided in Fig. 2.

Once confidence intervals are established for two MWFs evaluated at the same operating condition on the same workpiece, it is possible to determine whether the

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Table 1—The Relative Impact of Different Sources of Variability on Tapping Torque Observations from a Compilation of Tapping Torque Responses under Identical Test Conditions (M6 Tools; 1000 rpm)		
Condition	Statistically Significant?	Ranking of Significance
Fluid Type	yes	1
Tool Coatings	yes	2
Workpiece to Workpiece Variation	yes	3
Tool to Tool Variation (same geometry, coating)	yes	4

MWF performance differences are statistically significant using the t-test, which can be expressed as *(14)*,

$$t_{N_1+N_2-2,\alpha} = \frac{(\bar{\bar{X}}_1 - \bar{\bar{X}}_2)}{\sqrt{\frac{S_1^2}{N_1-1} + \frac{S_2^2}{N_2-1}}} \qquad [3]$$

Given the α level of confidence, one can calculate the observed t-value by Eq. [3] and compare the value to a standard table to determine whether the t-value is large enough to be considered significant, indicating that a statistically distinguishable difference in MWF performance exists.

DESIGN AND ANALYSIS OF T³ EXPERIMENTS ON MULTIPLE EVALUATION SYSTEMS

A statistical analysis of data from approximately 1200 experiments performed by the authors using M6 tools at 1000 rpm has shown that fluid type, tool coatings, workpieces, and tools all significantly affect tapping torque responses (Table 1). In light of these data, and similar findings widespread in the literature, one must account for each of these variables explicitly during T^3 experimental design. For MES, this means performing a comparison of two or more fluids on a single workpiece whenever possible and using a single tool to conduct tests in a random experimental order. At the same time, the following conditions must be held: 1) tool wear must be closely monitored and controlled with a strict tool change policy; and 2) experiments performed after the tool is broken-in must be repeated later in the run to verify that tool wear has no observable influence on the measurement of tapping torque.

Such modifications to ASTM D 5619 *(11)* for T^3 should be considered by practitioners working with MES. Naturally, variability-reducing activities within the standard should be maintained. For instance, tools must be broken-in, workpiece and tools must be cleaned, and a wire plug gage must be employed to ensure that the tool is centered in the pre-drilled and pre-reamed hole. However, based on the data observed during this investigation, the standard practice of delaying tool changes until built up edge (BUE) has accumulated is not recommended. By then, extraneous sources of variation are already influencing the comparisons of MWF. As an alternative, one can change tools and workpieces concurrently since workpiece variation is already known to be a variable significantly impacting tapping torque values. The more frequent tool changes only modestly increase testing costs, as tools were observed to account for only about 10% of MES costs when tool replacement occurred simultaneously with the workpieces.

Given that a new workpiece is not required for each MWF evaluation in MES, one must determine the minimum number of replicates of each test condition (N) that will yield a confidence interval of the desired size to distinguish reasonable differences in MWF performance. The minimum number of replicates can be calculated by setting the desired size of the confidence intervals, estimating the standard deviation ($S_{\bar{x}}$) of T^3 based on historical data under similar conditions, and rearranging Eq. [2] to solve for N. Based on thousands of tests with M4 and M6 tools with different coatings, the authors found that N from 20-30 was necessary for good resolution of MWF differences.

Another consideration when using MES is whether and when to use the concept of tapping torque "efficiency" advocated by ASTM D 5619 and defined by Eq. [4],

Tapping Torque Efficiency,

$$\% = h = 100 \text{ x } \frac{\bar{X}_{reference\ condition}}{\bar{X}_{test\ condition}} \qquad [4]$$

In fact, it can be shown that if two MWFs are evaluated on a single workpiece in MES, then using efficiency as a metric reduces the sensitivity of the comparison due to the introduction of error in the estimation of $\bar{X}$ for the reference condition. However, when comparing across workpieces, as is always the case when using SES, the efficiency metric is necessary. For MES, efficiency should only be used when test conditions from multiple workpieces are being compared.

Although efficiency calculations are generally necessary for MWF evaluation, ASTM D 5619 does not describe how confidence intervals can be calculated for efficiency. The determination of confidence intervals for efficiency is complicated by the fact that the observed tapping torque responses of the test and reference conditions are probability distributions with a quotient that cannot be easily described analytically. While this means that a simple confidence interval equation such as Eq. [2] cannot be derived, a reasonably simple algorithmic approach can be adopted as follows. To start, $\bar{\bar{X}}$ is calculated for both the test condition and the reference condition. A standard deviation for the plateau averages is also calculated ($S_{\bar{x}}$) for the test condition and the reference condition. $\bar{\bar{X}}$ and $S_{\bar{x}}$ are used as estimates for the mean and standard deviation of a normal distribution that serves as a statistical model of tapping torque outcomes for each MWF. Then, a common software spreadsheet can be used to numerically simulate a large number of experimental outcomes for both the test and reference MWFs (Fig. 3(a)). Random pairs of outcomes from each distribution are then taken to form simulated outcomes for efficiency, as plotted in Fig. 3(b). By plotting the cumulative probability distribution of the simulated output, the confidence interval for efficiency can be estimated. The

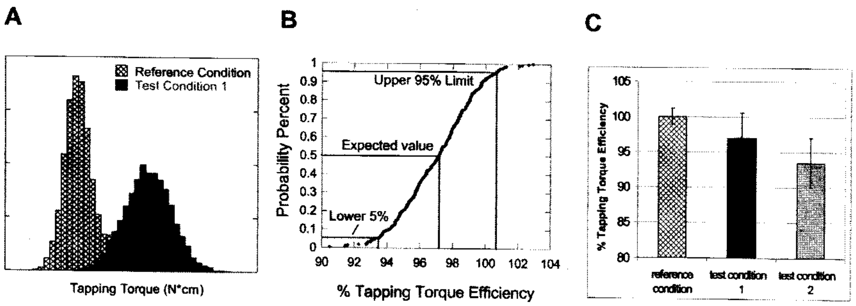

Fig. 3—By calculating 300 values of efficiency (b) from simulated normally distributed random variables of test condition and reference fluid (a), the desired confidence interval can be determined graphically (b). Repeating this procedure for subsequent test conditions allows for the direct comparison of MWFs across different workpieces (c), as long as the same reference fluid has been used for all fluids.

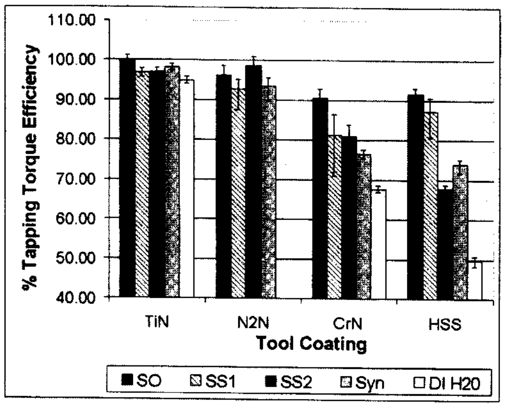

Fig. 4—Tapping torque efficiency values for four (4) high speed steel M6 taps of identical geometry with titanium nitride (TiN) coating, basic nitride coating (N2N), chromium nitride coating (CrN), and no coating (HSS) for a soluble oil, 2 semi-synthetic, and a synthetic MWF as well as deionized water. All experiments were performed at a machining speed of 1000 rpm across four workpieces. Results for N2N and deionized water was not feasible due to clogs and tool breaks and are not reported.

best estimate of the true efficiency quotient ($\mu_{efficiency}$) occurs at $\bar{\bar{X}}_{reference\ condition}/\bar{\bar{X}}_{test\ condition}$. This procedure can be repeated for other test conditions, allowing for the direct comparison of T^3 results across workpieces with confidence intervals as shown in Fig. 3(c).

EXPERIMENTAL SETUP AND RESULTS

To test the efficacy of MWF comparisons using the proposed experimental approach for MES, experiments described in this paper were carried out using a tapping machine with variable feed and speed settings and a maximum torque of 700 N•cm. The workpiece holder was designed such that the metal bar workpiece was fixed at both ends. The 1018 cold rolled steel bars were pre-drilled and pre-reamed with varying numbers of holes depending on the manufacturer. High-speed steel taps of identical geometry, 60° pitch and 3 straight flutes, in both M6 and M4 sizes, were used with four (4) coating conditions: uncoated (HSS), basic nitride coating (N2N), chromium nitride coating (CrN), and titanium nitride coating (TiN). A machining speed of either 500 rpm or 1000 rpm was used.

As a first analysis of the proposed approach to MES T^3 experimentation, the impact of tool coating, tool size, MWF type, and machining speed on tapping torque was examined (M6, 1000 rpm). The results of 340 individual cuts over 19 distinct conditions shown in Fig. 4 indicate that, in general, TiN tools perform better than the other tools and the soluble oil performs better than the other MWFs. It is difficult to establish other generalized trends in fluid performance under these testing conditions, but more specific conclusions can be drawn for individual tools. For instance, while MWF differences are clear and obvious when using HSS and CrN tools, they are practically indistinguishable for TiN and N2N tools.

Interestingly, different operating conditions impact the ability of the tool to statistically distinguish fluid differences. For instance, a comparison of Fig. 5(b) and Fig. 4 reveals that while CrN tools revealed fluid differences at 1000 rpm, they did not at 500 rpm. In fact, the 500 rpm conditions examined in Fig. 5 show very little ability to distinguish MWFs. A comparison of Figs. 5(a) and 5(c) to Fig. 4 also reveals that when M4 tools are used HSS offers increased tapping torque efficiency over TiN for all MWF types regardless of machining speed. From these observations, it is clear that certain T^3 test conditions respond differently to MWF/tool combinations than others. Consequently, multiple conditions must be evaluated to fully understand the impact of different MWF/tool combinations, and great care should be taken to understand how test conditions relate to the field operations in which the MWF is to be used. Furthermore, general claims about MWF performance can only be derived from statistically

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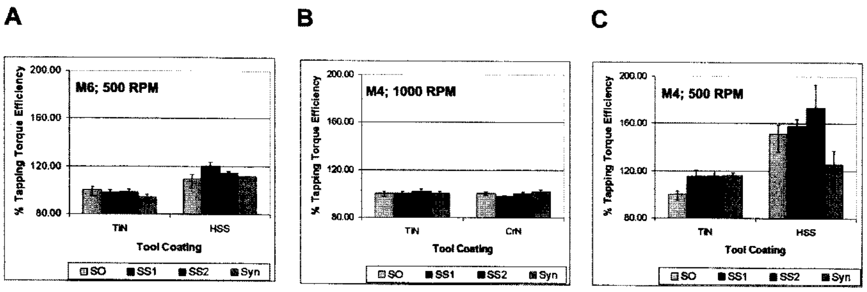

Fig. 5—Tapping torque efficiency values for (a) TiN and uncoated high speed steel (HSS) M6 taps at 500 RPM, (b) TiN and CrN coated M4 taps at a machining speed of 1000 rpm and (c) TiN and uncoated HSS M4 taps at 500 rpm. For each condition, a soluble oil, 2 semi-synthetics, and a synthetic metalworking fluid were investigated.

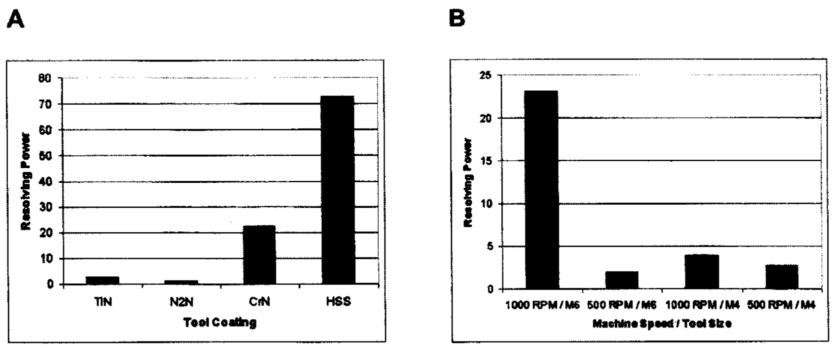

Fig. 6—Resolving power as (a) a function of tool coating with M6 tools at a machining speed of 1000 rpm (including results for deionized water) and (b) a function of machine speed and tool size for uncoated tools (HSS) (not including deionized water). The inclusion of deionized water increases resolving power in magnitude, as demonstrated by a comparison of (a) and (b), demonstrating that standardized fluids must be used for determining resolving power.

significant results under variable operating conditions, tool coatings, and workpiece materials.

RESOLVING POWER: A METRIC OF SENSITIVITY

Given differences in MWF performance under different T^3 operating conditions, it is important to quantify the ability of a given condition to detect differences in MWF performance. To facilitate this, Eq. [5] defines a metric of resolving power that aims to quantify the sensitivity of T^3 to different MWFs at a fixed operating condition,

Resolving Power =

$$\frac{\hat{\sigma}^2_{between\ fluids}}{\hat{\sigma}^2_{within\ a\ fluid}} = \frac{\frac{\sum_{i=1}^{r}(\bar{\bar{X}}_i - \bar{\bar{X}})^2}{r-1}}{\frac{\sum_{j=1}^{s}(\bar{X}_j - \bar{\bar{X}})^2}{s-1}} \qquad [5]$$

where $\hat{\sigma}^2_{between\ fluids}$ provides an estimate of variability across MWFs, and $\hat{\sigma}^2_{within\ a\ fluid}$ estimates the variance of plateau averages for a single fluid. In Eq. [5], $\bar{X}$ is the average of plateau values in a single experiment (Fig. 1), $\bar{\bar{X}}$ is the average of all $\bar{X}$ observed for a single MWF, $\bar{\bar{X}}$ is the average of all $\bar{X}$ for all MWFs, r is the number of MWFs tested at the operating condition, and s is the number of replicate tests per MWF.

As is evident from Eq. [5], the resolving power has two distinct components: the numerator is related to the average size of the confidence interval while the denominator is related to the degree of difference in tapping torque response for different MWFs observed under the specific operating condition investigated. The ratio of these values is a metric of discriminatory power of the MWF at the operating condition. The resolving power for each test condition shown in Figs. 4 and 5 was calculated by Eq. [5] with results indicating that the uncoated tool (HSS) is the most sensitive to differences in MWF type for the speeds, workpieces, and MWFs analyzed. The resolving power values are plotted in Fig. 6.

After the selection of HSS tools for increased T^3 sensitivity, the resolving power of HSS tools was then determined as a function of machining speed and tool size. As shown in Fig. 6(b), experiments with M6 tools at 1000 rpm

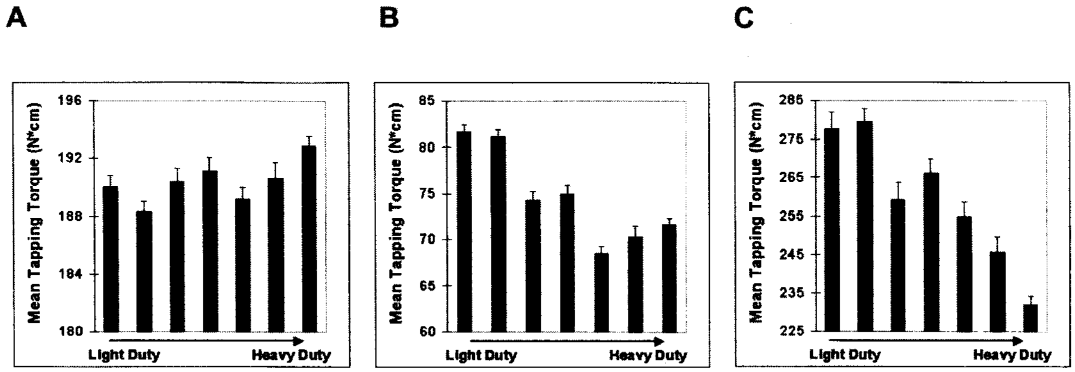

Fig. 7—Tapping torque results as a function of MWFs ranging from light to heavy duty. Tapping torque tests were performed at 1000 rpm with (a) M6 TiN tools (resolving power = 0.83), (b) M4 HSS tools (resolving power = 3.96), and (c) M6 HSS tools (resolving power = 23.14) of identical geometry.

were the most sensitive test conditions for HSS tools and 1018 cold rolled steel workpieces. For this case, the numerator is driving the high resolving power value with large differences in T^3 efficiencies between fluids, ranging from ~49% for deionized water to ~91% for the soluble oil reference MWF (Fig. 4). A range of fluids from deionized water to soluble oil was utilized in order to cover the range of expected MWF performances. These fluids became a standard set of fluids that were used to calculate resolving power. As with all aspects of MWF evaluation, standardization is necessary for consistent interpretation and comparisons of resolving power metrics.

CORRELATION OF TAPPING TORQUE RESPONSE WITH FIELD PERFORMANCE

Based on Fig. 6 it is evident that operating conditions can either mask MWF performance (low resolving power) or provide the means to differentiate between MWF types (high resolving power). If T^3 experimental conditions with low resolving power are selected, it may be impossible to differentiate MWFs, even where known differences exist. To illustrate this, seven (7) MWFs varying from light duty to heavy duty were examined using MES T^3. The MWF duty ratings were based upon the extensive field experience of a major MWF supply company. For M6 TiN tools at 1000 rpm, it was found that even the MWF with the lowest duty rating could not be statistically distinguished from the MWF with the highest duty rating (Fig. 7(a)). However when conditions were chosen with a higher resolving power (e.g., M4, HSS, 1000 rpm), fluid differences were easily distinguishable and the T^3 responses were very well correlated with the expected trend of MWF field performance (Fig. 7(b)). At the test condition with the highest resolving power (M6, HSS, 1000 rpm), the expected field performance was captured even more clearly (Fig. 7(c)).

In order to quantify the relationship between laboratory T^3 resolving power and expected field performance, a correlation coefficient ($\rho_{x,y}$), for each operating condition was calculated as Eq. [6],

$$\rho_{X,Y} = \frac{cov(fluid\ duty, \bar{X})}{S_{fluid\ duty} \cdot S_{\bar{X}}} \quad [6]$$

where the numerator is the covariance between the fluid duty (evenly scaled from 1 to 7) and the average tapping torque response at the given test condition. $S_{\text{fluid duty}}$ and $S_{\bar{X}}$ are the estimated standard deviations of the fluid duty and the average tapping torque responses, respectively.

The correlation coefficients provided in Table 2 indicate the extent to which the selected T^3 operating condition captures the expected field performance. The correlation coefficients clearly show that as resolving power increases, the field performance trend of the MWFs is better predicted. Since a higher duty MWF should produce a lower tapping torque, the correlation coefficient is ideally -1. Where the correlation coefficient is far from -1, the resolving power is low and MWF differences are not statistically significant. Consequently, one can conclude that resolving power is a useful indicator to quantify the ability of a T^3 condition to capture field performance.

TRADE-OFF BETWEEN RESOLVING POWER AND COST

Naturally, there is a trade-off between 1) reducing time, material, and cost of T^3 experimentation, and 2) acquiring statistically significant results. Accordingly, test conditions must be selected such that the tapping torque test yields useful results with a minimum number of necessary repetitions to minimize costs. In other words, increasing resolving power through additional testing must be justified economically.

For the experimental setup used in this investigation, a workpiece cost approximately $150, whether pre-drilled and pre-reamed with 240 M6 holes or 416 M4 holes, and tools ranged in cost from $30-$35 for M6 to $25-$30 for M4 (depending on the coating). Based on these figures,

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Table 2—Correlation between Expected Maetalworking Fluid Field Performance and Tapping Torque Results at 1000 rpm with (a) M6 TiN, (b) M4 HSS, and (c) M6 HSS Tools of Identical Geometry					
	Duty	M6, TiN 1000 rpm	M6, HSS, 1000 rpm	M4, HSS, 1000 rpm	Resolving Power
M6, TiN, 1000 rpm	0.63	1.00			0.83
M4, HSS, 1000 rpm	-0.87	-0.37	1.00		3.96
M6, HSS, 1000 rpm	-0.95	-0.73	0.82	1.00	23.14

Table 3—Standard Deviation Values for Tapping Torque Test Results as a Function of Tool Coating and Size at 1000 rpm with a Soluble Oil Reference Fluid, the Number of Repeated Holes Necessary Per Test Condition for the Desired Level of Confidence (90% or 95%), and Associated Material (Tool and Workpiece) Costs.

Tool Type	Tool Size	Std. Dev.	N From Eq. [2] (90% Confident)	Cost at 90%	N From Eq. [2] (95% Confident)	Cost at 95%	Resolving Power (N=17)
TiN	M6	2.7	~19	$17.48	~30	$27.60	0.83
TiN	M4	3.6	~30	$16.20	~45	$24.30	2.60
HSS	M6	4.1	~35	$32.20	~55	$50.60	23.14
HSS	M4	4.4	~48	$25.92	~69	$37.26	3.96

evaluating MWFs with M4 tools is more economical per test given that nearly 60% more tests can be conducted on a single workpiece for a cost of $0.54 per M4 hole compared with $0.92 per M6 hole. Although individual M4 tests are less expensive than M6 tests, more repetitions are required to achieve the same level of confidence as shown in Table 3. Table 3 also indicates that uncoated (HSS) tools offer better fluid differentiation ability, but require more replicates to achieve a given confidence interval size when compared with other tool coatings. Interestingly, the most expensive test condition (HSS, M6, 1000 rpm) offers the highest resolving power and therefore the most sensitive T^3 condition for MWF evaluation. While this result advocates an economic investment to improve data quality, it must be assumed that determining and applying high resolution testing conditions for MWF evaluation is a more competitive strategy. The alternative is to perform a multitude of T^3 experiments that result in data that cannot be interpreted, or worse, result in data that may be misleading.

CONCLUSIONS

The traditional procedure for conducting tapping torque tests (T^3) has been evaluated in the context of multiple evaluation systems (MES) where multiple tests are performed on a single workpiece. Since ASTM D 5619 was not designed for MES, a modified approach to MWF evaluation was found to be necessary to fully realize the potential for improved T^3 resolution. Using ASTM D 5619 as a starting point, recommended experimental considerations were established for MES. These were critically analyzed with the following conclusions reached:

- High performing tools reduce or eliminate MWF differences, which makes such tools ineffective for the evaluation of MWF performance. Tool coatings are inadvisable for MWF evaluation unless they will be used exclusively in the field under low wear conditions.
- The effectiveness of the tool coating can depend on tool size. For instance, uncoated high speed steel tools (HSS) performed consistently better than TiN tools for M4 tools, while TiN coatings performed consistently better for M6 tools.
- MWF selection for optimal performance cannot be based on T^3 responses at a single condition. General conclusions about the performance of a fluid can only follow from consistent performance results across different test conditions.
- A resolving power metric was defined as a quantitative measure of the ability of an operating condition to discriminate between MWFs. As resolving power increases, the correlation of T^3 response to expected field performance increases.
- Designing T^3 experiments on the basis of minimizing cost per test can lead to poor or misleading conclusions about the potential functionality of MWFs under manufacturing conditions. Tapping torque experimentation must be planned systematically and deliberately to maximize the strategic value of each test.

ACKNOWLEDGMENTS

This research was funded by the United States National Science Foundation under DMI-0093514. The authors wish to thank D.A. Stuart Co. (Naperville, IL) for providing materials used in this project.

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