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Evaluating Metalworking Fluids Tapping Torque Test

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润滑工程

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Evaluating Metalworking Fluids 转矩测试

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Technical Paper

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) to be performed on a single workpiece have been gaining in popularity for the evaluation of metalworking fluids (MWEs). 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$_3$ resolving power, and statistical significance of T^3 results.

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NOMENCLATURE

CI =confidence interval for a given cut, [N-cm]
N =number of replicate cuts at a given test condition
=number of torque values recorded for a single cut
=number of fluids evaluated at a given test condition
S =observed variance for a single cut, [N²·cm²
S =observed variance for a given test condition, [N²·cm²
=number of replicate cuts for a given fluid
=t-distribution ordinate
X =average torque value for the plateau region of a cut profile, [N-cm]
=average torque value for a given test condition, [Ncm]
=average torque value of all fluids for a given test condition, [N·cm]
=percent confidence
=percent tapping torque efficiency
p =correlation coefficient
Og =variance for a single cut, [N²cm²
$\hat{\sigma}$ =estimated variance for a given test condition, [N²cm²
μ =true torque value for a single cut, [N-cm]
=estimated torque value for a given test condition, [N·cm]

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基于扭矩测试法对金属加工液进行经济性评估的实验与统计设计考量

近期，允许多个测力扭矩测试在单个工件上进行的多评估系统（MES）在金属加工液（MWEs）评估领域日益受到青睐。然而，MWF 配方师难以获得具有统计学显著性或与现场经验相符的结果，这引发了对MES有效性的质疑。本文针对MES评估MWF 提出统计与实验设计考量，旨在最大化T ³对MWF 性能的敏感性，并提升实验室与现场性能之间的相关性。为此，我们开发了一种分辨力指标，用于量化T ³工作条件（速度、材料、刀具尺寸等）区分不同MWFs的能力。研究表明，随着分辨力的提升，T ³对预期现场性能响应的相关性也随之增强。本文最后讨论了提高cost₃解析能力与T ³结果统计显著性之间的经济权衡关系。

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命名法

CI
N

=给定切割条件下的置信区间，[N-cm]=特定测试条件下重复切割次数=单次切割记录的扭矩值数量=特定测试条件下评估的流体数量=单次切割观测方差，

S
S

[N 2·cm 2=特定测试条件下的观测方差，[N 2 ·cm 2=特定流体的重复切割次数

-t分布纵坐标

X

=切割轮廓平台区域的平均扭矩值，[N-cm]=给定测试条件下的平均扭矩值，[Ncm]

=给定测试条件下所有流体的平均扭矩值，[N·cm]=置信度百分比

=百分比击打扭矩效率

=相关系数

p
Og

=单次切割的方差，[N 2 cm 2

=给定测试条件下的估计方差，[N 2 cm 2=单次切割的真实扭矩值，[N-cm]

μ

=给定测试条件下的估算扭矩值，[N·cm]

最终稿件于2003年2月12日获得批准
Jerry Byers主导的综述

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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 D4172)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^3has 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 ASTMD5619 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 inT^3results reported in the literature(1),(2),(9),(I^1),(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 aT^3 experiment.

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

ASTMD5619 was designed for T^3systems 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^3potentially 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 D5619 was not designed for MES,additional considerations are discussed below that assist in capitalizing upon the unique opportunities afforded by multiple evalua~~tions on a single workpiece.~~

MEASURING VARIABILITY AND CONFIDENCE IN

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(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 a 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,ta,n-1 is the t-distribution ordinate corresponding to the alevel of confidence given n-1 degrees of freedom,and S is the estimated standard deviation about X.Equation [1]represents a quantified expression of the degree of certainty that can be associated with the estimate of μ by X observed experimentally.

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

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关键词

金属加工液评估；攻丝；机械加工；经济学；刀具涂层；应用统计学

引言

针对金属加工液（MWF）现场性能评估的有效实验室测试方法探索已持续超过50年。标准实验室磨损试验与极端压力试验（如销钉与V型块评估试验ASTM D 2670、四球磨损试验ASTM D4172）应用范围有限，且未能被证实能充分反映实际生产工况下的加工性能(1)-(3)。事实上，大量文献证据表明，只有通过实际加工操作（如扩孔、钻孔或攻丝）才能合理预测金属加工液在切削作业中的润滑性能(1)、(4)-(8)。显然，测试条件越接近实际生产工况，其预测效果越好。但在配方研发初期阶段，仍需建立能简化开发流程的有效实验室测试方法。在为实现这一目标而开发的众多实验室规模性能测试中，攻丝扭矩测试（T 3）因其满足多项理想测试要求而获得广泛认可：(a)与现场测试结果具有相关性，(b)操作简便，(c)测试速度快，(d)经济高效，(e)测试样本量小，(f)测量精度高，(g)能适应严苛工况(9)。此外研究证实，低攻丝扭矩与工具寿命延长、螺纹表面完整性良好以及高效金属加工液之间存在显著相关性(2)、(6)、（10）。

根据ASTM D 5619《使用扭矩测试机比较金属去除液的标准》（11），“[扭矩测试]方法相较于以往可用的实验室规模测试，能更准确地预测金属去除液的润滑性能。”但需注意的是，ASTM D 5619并未规定默认操作条件，包括加工速度、工件材料、刀具合金、刀具尺寸或刀具涂层。可以合理推测，由于未考虑此类可控变量，以及工件硬度和刀具磨损等不可控变量，导致文献中报道的T 3结果存在显著差异(1)、(2)、(9)、（I 1）、（12）。与这些观察结果一致，MWF 配方师在获取具有统计学意义的结果或基于经验预期结果方面均面临困难。这引发了对T 3在金属去除液评估中有效性的质疑。

本文研究了能有效最小化3中变异来源的实验设计方法，并提出一种可提升攻丝扭矩实验评估 MWF 性能效能的实验设计范式。具体而言，本研究：(a)提出利用新型攻丝扭矩测试平台设计、实施及解读 MWF 评估实验的方法；(b)论证了操作条件与加工参数的选择对通过攻丝扭矩测试区分 MWF 性能及预测实际工况表现具有关键作用；(c)明确了设计3实验时成本与灵敏度之间的权衡关系。

单次评估系统（SES）与多次评估系统（MES）对比

ASTMD5619标准专为T 3系统设计，该系统采用对每个工件进行单次抽样评估（SES）。由于不同工件间的差异可能掩盖由多工件因素（MWFs）引起的扭矩响应差异，每次对新工件进行测试评估都会给评估过程引入显著不确定性。为消除这种影响，SES操作员通常会尽量选用同一批次、同制造商生产的工件进行测试，但有时这会带来较高成本。

由于工件尺寸差异和单次测试成本带来的挑战，人们开发了攻丝扭矩测试平台·，~~该平台可在同一工件（MES）上评估多种测试条件~~。虽然这种设计通过减少工件材料相关变异性使T 3更具便利性和成本效益，但考虑到单个工件内可能出现刀具磨损和局部硬度差异，此类系统在实验设计与结果解读方面带来了新挑战。鉴于ASTM D5619标准并非针对MES设计，下文将探讨有助于充分利用单工件多次评估独特优势的额外考量因素。

测量变异性与置信度

打孔装置通常会输出随深度变化的扭矩测量值，从而形成如图1(a)所示的切削扭矩曲线。根据中心极限定理的预期（图1(b)），在曲线平台区域（理论上不存在进给力、退给力或切屑堵塞等系统性或明显变异因素）的扭矩值分布应遵循正态分布。平台区域切削扭矩值的平均值(X) 可作为所选工况 （μ） 下理想“真实”打孔扭矩的参考值。考虑到平台区域数据点数量相对较少，正态分布可采用t分布进行近似处理，其置信水平为a的 μ 置信区间可通过公式(13)表示。

置信区间 $$, CI = \bar{X} \pm r_{\alpha,n-1} \times \frac{S_x}{\sqrt{n}} \qquad [1]$$

其中n表示平台期切割扭矩值的数量，ta，n-1是对应于n-1自由度下a水平置信度的t分布纵坐标，S表示X的估计标准差。公式[1]量化了实验观测到的X对 μ 估计值所体现的确定性程度。

在单次检测中，n值受限于检测深度与仪器分辨率，且由于Sis值通常较大，

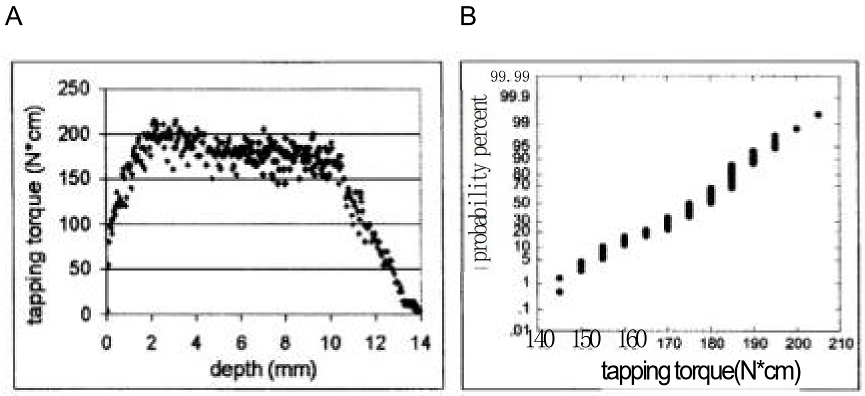

Fig.1—(a)A typical cutting profile with the plateau region indicated (bolded dots)and (b)a normal probability plot of the tapping torque values in the plateau region.Although the testbed applied in this research can only resolve tapping torque to a resolution of 5 N*cm,the close fit(R^2=0.98)of (b)to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

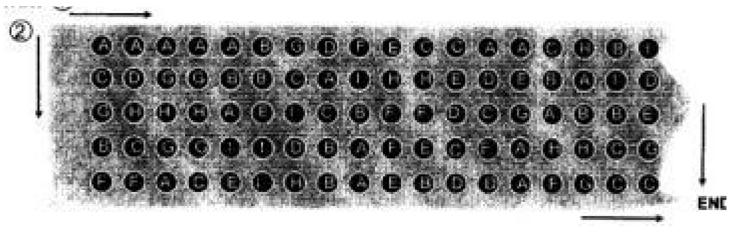

Fig.2—Sample randomization of T³ conditions on a workpiece where the letter indicates a test condition for evaluation (tool/fluid combination)and the arrows indicate the order of evaluation (left to right across a row;then top to bottom down the workpiece).“A”represents the reference test condition used 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 录,which is the average of all the plateau values observed over multiple tests at the operating condition under consideration.The confidence interval for x is described by,

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

Equation [2]captures the fundamental trade-off in designing T³experiments:the higher the uncertainty inherent to the experimental design(Sz),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 MWFevaluations 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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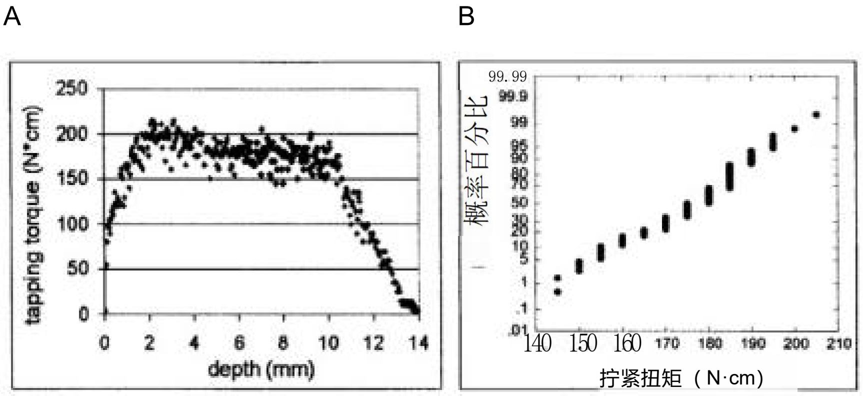

图1—(a)典型切割剖面图，其中平台区域已标出（加粗圆点）；(b)平台区域内攻丝扭矩值的正态概率分布图。尽管本研究采用的试验台仅能以5 N*cm的分辨率解析攻丝扭矩，但(b)图与线性关系的高拟合度（R 2=0.98）表明平台区域的结果可合理采用正态分布进行表征。

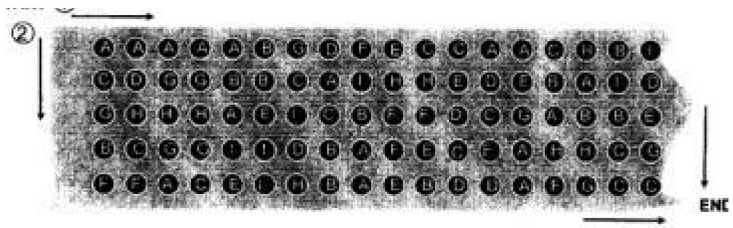

图2——工件上T 3工况的样本随机化示意图，其中字母表示待评估的测试工况（刀具/流体组合），箭头指示评估顺序（从左至右沿行排列；再从上至下沿工件方向排列）。“A”代表用于刀具磨合期及效率计算的基准测试工况。通过对比初始阶段与末期阶段的“A”测试结果，可判断刀具磨损是否对实验结果产生显著影响。

由此可以得出，由等式[1]确定的置信区间通常过大，无法区分不同 MWF 公式之间的差异。因此，在MES中会对给定操作条件进行多次重复测试(N)。通过多次测试，可获得真实抽吸扭矩的最佳单点估计值。(μ)is 录该数值为在所考虑的操作条件下多次测试中观测到的所有平台值的平均值。x的置信区间由以下公式描述：

置信区间

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

公式[2]揭示了设计T 3实验时的核心权衡关系：实验设计固有的不确定性（Sz）越高，就需要进行更多测试(N)，才能将置信区间缩小到足以检测 MWF 配方性能差异的程度。换言之，虽然重复测试会延长评估时间和成本，但能显著提升对 MWF 差异的敏感度——这正是 MWF 性能实验室评估过程中所追求的目标。

实验重复设计有助于均衡分散不可控变异来源（例如工件局部硬度和刀具磨损），只要实验按随机顺序进行，就能确保所有微晶铁合金（MWFe）评估结果的可靠性。随机化方法旨在将未知且不可控的变异因素均匀分布于实验设计中，从而降低局部效应的影响，减少实验因未知随机因素导致结论偏差的风险。图2展示了MES（微观结构评估）的样本随机化模式示例。

当针对同一工件在相同操作条件下评估的两个MWF（机械工作函数）建立置信区间后，即可确定其是否具有统计学意义。

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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 a level of confidence,one can calculate the observedt-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 OFT^{3}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 ffect 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 D5619(11)for T^{3}should be considered by practitioners working with MES. Naturally,variability-reducing activities within the tandard 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 accumulatedis 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元) of T^{3}based on historical data under similar conditions,and rearranging Eq.[2]to solve for N. Based on thousands oftests 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 ASTMD5619 and defined by Eq.[4],

Tapping Torque Efficiency,

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

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 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 MWFevaluation,ASTMD5619 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 ofthe 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,x is calculated for both the test condition and the reference condition.A standard deviation for the plateau averages is also calculated(S元)for the test condition and the reference condition. $\bar{\bar{x}}$ and Sz 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

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表^1——不同变异来源对敲击扭矩观测值的相对影响：基于相同测试条件下敲击扭矩响应数据的综合分析
(M6 TooLS；1000 rpm)

条件	统计学上 显著性?	排名 意义
流体类型	对	1
工具涂层	对	2
工件间变异	对	3
工具间差异（相同几何结构，涂层）	对	4

采用t检验分析显示， MWF 性能差异具有统计学显著性，可表示为(14)。

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

在给定置信水平的情况下，可以通过等式[3]计算观察到的t值，并将该值与标准表进行比较，以确定t值是否足够大以被视为显著，这表明 MWF 性能存在统计学上可区分的差异。

多评估系统中OFT^{3}实验的设计与分析

通过对作者使用M6工具在1000转/分钟转速下进行的约1200次实验数据进行统计分析发现，流体类型、工具涂层、工件及工具本身都会显著影响攻丝扭矩响应（表1）。基于这些数据以及文献中广泛报道的类似结果，在T 3实验设计中必须明确考虑所有变量。对于MES工艺而言，这意味着应尽可能在单个工件上对比两种及以上流体，并采用单一工具以随机实验顺序进行测试。同时需满足以下条件：1）必须严格监控工具磨损情况并实施严格的换刀策略；2）工具磨合期后的实验需在后续工序中重复进行，以验证工具磨损对攻丝扭矩测量结果无显著影响。

对于T 3的ASTM D5619(11)标准进行此类修改时，使用MES系统的从业者需予以考虑。当然，标准中降低变异性的措施仍需保持。例如，工具必须经过磨合期、工件与工具需定期清洁，并使用导丝规确保工具在预钻孔和预扩孔中居中定位。但根据本次调查观察数据，建议不要沿用传统做法——即等到累积加工余量（BUE）形成后再更换工具。此时，其他变异来源已开始影响 MWF 对比结果。作为替代方案，可同步更换工具与工件，因为已知工件变异是显著影响测量结果的关键变量。在攻丝扭矩值方面，工具更换频率越高，测试成本仅略有增加，因为当工具更换与工件同步进行时，工具更换仅占MES成本的约10%。

鉴于MES系统中每次 MWF 评估无需更换新工件，必须确定每个测试条件的最小重复次数(N)，以获得所需大小的置信区间，从而区分 MWF 性能中的合理差异。最小重复次数可通过设定置信区间的期望大小、基于类似条件下的历史数据估算T 3的标准差（S元），并重新排列等式[2]求解N来计算。根据对不同涂层的M4 和M6 工具进行的数千次测试，作者发现N 值为20-30时能有效分辨 MWF 差异。

使用MES时需考虑的另一因素是是否及何时采用抽吸扭矩“效率”这一概念。

由ASTMD5619倡导并由等式[4]定义的抽头扭矩效率，

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

实际上可以证明，若在MES系统中对单个工件进行两个MWF（多变量函数）评估时，采用效率作为评估指标会因参考条件X值估算误差的引入而降低比较结果的敏感性。然而在跨工件比较时（这在SES系统应用中始终是常态）， 效率指标仍不可或缺。对于MES系统而言，仅当需要对比多个工件的测试条件时，才应采用效率指标进行评估。

尽管效率计算通常是MWFevaluation的必要步骤，但ASTM D5619并未描述如何计算效率的置信区间。效率置信区间的确定因测试条件与参考条件下的观测抽头扭矩响应具有难以解析描述的商比概率分布而变得复杂。虽然这意味着无法推导出如等式[2]这样的简单置信区间公式，但可采用如下较为简单的算法方法：首先分别计算测试条件与参考条件下的x值，同时计算测试条件与参考条件下的平台平均值标准差（S元）。$\bar{\bar{x}}$ 其中Sz值用于估计正态分布的均值和标准差，该分布作为各 MWF 打孔扭矩结果的统计模型。随后可使用通用软件电子表格对测试型与参考型MWF（ 图3 (a)）进行大量实验结果的数值模拟。从每个分布中随机选取结果对，构建效率参数的模拟数据（如图3(b)所示）。通过绘制模拟输出的累积概率分布曲线，可估算效率参数的置信区间。

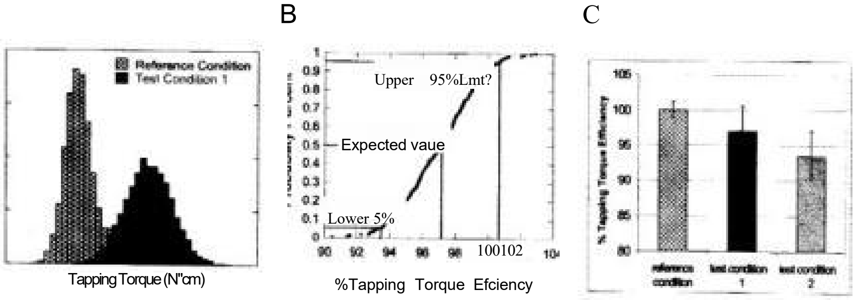

Fig.3—By calculating 300 values of efficiency (b)from simulated normally distributed random variables of test condition and reference fluid(a),the desired confidence interval can be determined graphically (b).Repeating this procedure for subsequent test conditions allows for the direct comparison of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

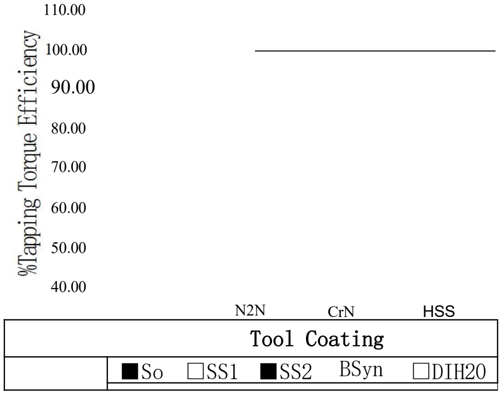

Fig.4—Tapping torque efficiency values for four(4) high speed steel M6 taps of identical geometry with titanium nitride (TiN)coating,basic nitride coating(N2N),chromium nitride coating(CrN), and no coating(HSS)for a soluble oil,2 semi-synthetic,and a synthetic MWF as well as deionized water.All experiments 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 (Peficienc) occurs at xreference gondition/×test condition.This procedure can be repeated for other test conditions,allowing for the direct comparison of T^3results 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^3test 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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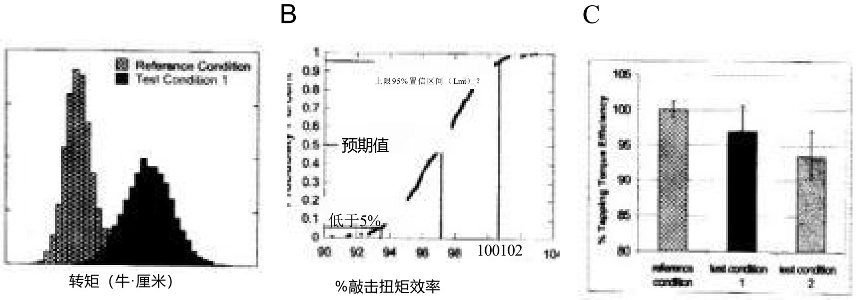

图3——通过计算测试工况与参考流体(a)的模拟正态分布随机变量所得到的300个效率值(b)，可直观确定所需置信区间(b)。若后续测试工况重复此流程，只要所有流体均使用相同参考流体，即可实现不同工件间MWF值的直接对比(c)。

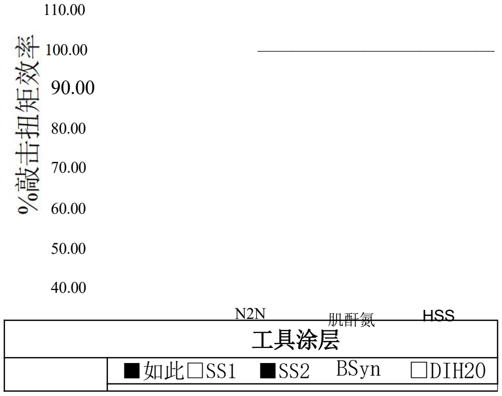

图4——四种几何形状相同的高速钢M6丝锥在可溶性油、两种半合成油、合成 MWF 及去离子水中的攻丝扭矩效率值对比，分别采用氮化钛（TiN）涂层、基础氮化物涂层（N2N）、氮化铬涂层（CrN）及无涂层（HSS）。所有实验均在1000 rpm的加工速度下对四件工件进行。由于堵塞和刀具断裂问题，N2N涂层与去离子水的实验结果不可行，故未予报告。

真实效率商数（Peficienc）的最佳估计值出现在x参考条件/×测试条件处。该方法可重复应用于其他测试条件，从而实现不同工件间T 3结果的直接比较，并附带如图3(c)所示的置信区间。

实验设置与结果

为测试采用所提出的MES实验方法进行 MWF 比较的有效性，本研究使用配备可变进给速度和转速设置、最大扭矩为700 N·cm 的攻丝机进行了实验。工件夹具设计为将金属棒工件两端固定。1018冷轧钢棒根据制造商要求预先钻孔和扩孔，孔数不等。使用相同几何形状、60°螺距和3条直槽的高速钢丝锥（M6和M4两种规格），并采用四种涂层条件：未涂层（HSS）、氮化物基础涂层（N2N）、氮化铬涂层（CrN）以及氮化钛涂层（<|sp_1>）。加工速度采用500 rpm或1000 rpm两种模式。

作为对MES T 3实验所提方法的首次分析，本研究考察了刀具涂层、刀具尺寸、 MWF 类型及加工速度（M6, 1000 rpm）对攻丝扭矩的影响。图4所示19种不同工况下340次单独切削结果表明，总体而言氮化钛刀具性能优于其他刀具，可溶性油液也优于其他金属水基液（MWFs）。在这些测试条件下难以确定流体性能的其他普遍趋势，但可针对特定刀具得出更具体的结论。例如，虽然使用高速钢（HSS）和碳化铬（CrN）刀具时 MWF 差异明显，但氮化钛与氮化氮（N2N）刀具之间的差异实际上难以区分。

有趣的是，不同的工作条件会影响工具在统计上区分流体差异的能力。例如，对比图5(b)和图4可以发现，虽然CrN工具在1000 rpm时能检测到流体差异，但在500 rpm时则无法做到。事实上，图5中考察的500 rpm工况显示其区分MWFs的能力极低。将图5(a)、5(c)与图4对比还可发现，当使用M4工具时，无论加工速度如何，高速钢在所有 MWF 类型中均比氮化钛具有更高的攻丝扭矩效率。这些观察结果表明，某些T 3测试条件对 MWF /工具组合的响应与其他工况存在差异。因此，必须评估多种工况以全面理解不同 MWF /工具组合的影响，并需谨慎分析测试条件与 MWF 实际应用环境之间的关联。此外，关于 MWF 性能的普遍性结论只能通过统计方法得出。

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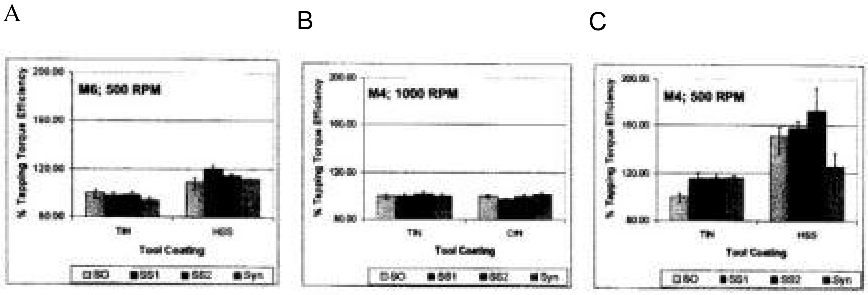

Fig.5—Tapping torque efficiency values for(a)TiN and uncoated high speed steel (HSS)M6 taps at 500 RPM,(b)TIN and CrN coated M4 taps at a machining speed of 1000 rpm and (c)TiN and uncoated HSS M4 taps at 500 rpm.For each condition,a soluble oil,2 semi-synthetics, and a synthetic metalworking fluid were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

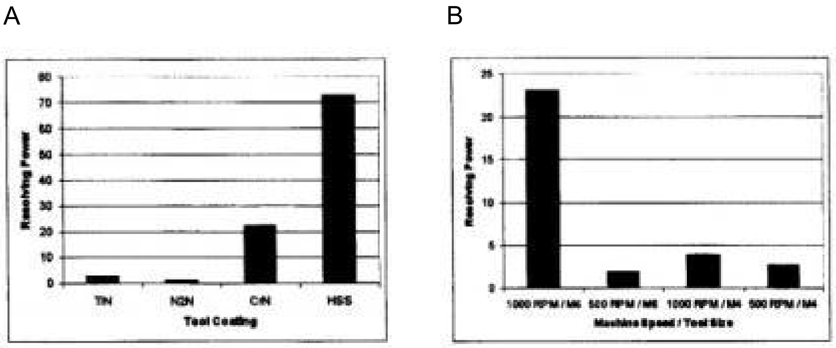

Fig.6—Resolving power as (a)a function of tool coating with M6 tools at a machining speed of 1000 rpm(including results for deionized water)and (b)a function of machine speed and tool size for uncoated tools (HSS)(not including deionized water).The inclusion of deionized water increases resolving power 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 T³operating 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 T³ 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],X is the average of plateau values in a single experiment(Fig.1),x is the average of all X observed for a single MWF, $\bar{\bar{X}}$ is the average of all 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 T³sensitivity,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

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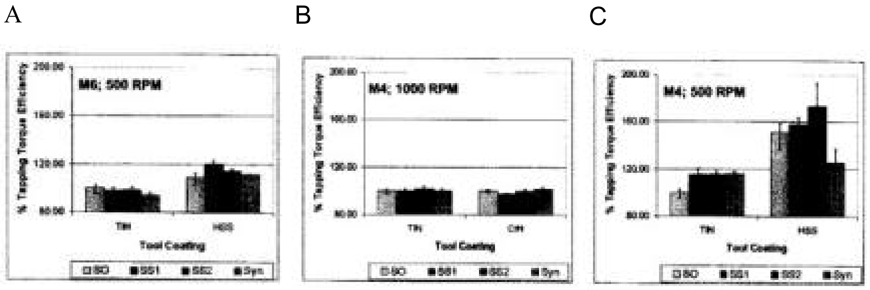

图5——(a)氮化钛与未涂层高速钢（ HSS） M6丝锥在500转/分钟下的攻丝扭矩效率值， (b)氮化钛与CrN涂层M4丝锥在1000转/分钟加工速度下的攻丝扭矩效率值， 以及(c)氮化钛与未涂层HSS M4丝锥在500转/分钟下的攻丝扭矩效率值。每种工况下均测试了可溶性油、两种半合成油及一种合成金属加工液。

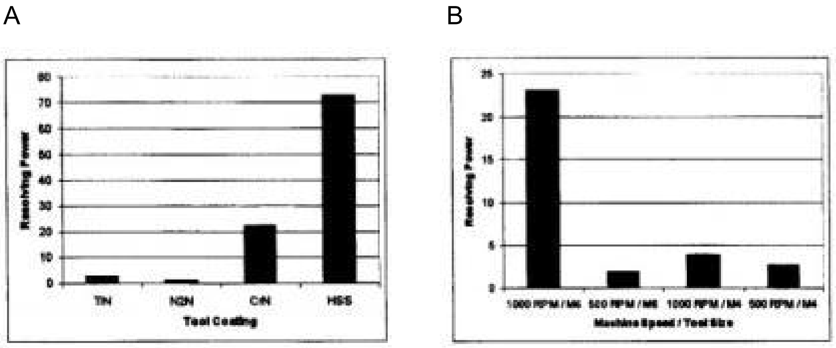

图6——分辨力随工具涂层变化的函数关系：(a)采用M6工具在1000转/分钟加工速度下的结果（含去离子水实验数据）；(b)未涂层工具（高硬质合金）在不同机床转速与刀具尺寸下的变化趋势（不含去离子水实验数据） 。通过对比(a)与(b)数据可见，添加去离子水会显著提升分辨力数值，这表明在测定分辨力时必须使用标准化液体介质。

在不同工况条件、刀具涂层及工件材料下均显示出显著结果。

解析能力：灵敏度的度量指标

鉴于不同T 3运行条件下 MWF 性能的差异，量化特定条件检测MWF 性能差异的能力至关重要。为此，等式[5]定义了一个分辨能力指标，旨在量化固定运行条件下T 3对不同MWFs的敏感性。

分辨力=

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

在 ......处 $\hat{\sigma}^2_{between\ fluids}$ 提供流体内部变异性的估计值，用于估算方差 MWFs, and $\hat{\sigma}^2$ 单一流体的平台平均值。在等式[5]中，X表示单次实验中平台值的平均值（图1），x表示单次 MWF 中所有观测值X的平均值。$\bar{\bar{X}}$是所有MWFs中所有X值的平均值，r表示在操作条件下测试的MWFs数量，s表示每个 MWF 的重复测试次数。

如等式[5]所示，分辨力具有两个明显组成部分：分子与置信区间的平均尺寸相关，而分母则与特定操作条件下观察到的不同MWFs（多维波动函数）在敲击扭矩响应中的差异程度相关。这些数值的比值是该 MWF 在操作条件下区分能力的度量指标。图4和图5中所示各测试条件的分辨力通过等式[5]计算得出，结果表明对于所分析的速度、工件和MWFs，未涂层工具（HSS）对 MWF 类型差异最为敏感。分辨力数值如图6所示。

在选定可提高T 3灵敏度的HSS工具后，进一步确定了HSS工具的分辨力与加工速度及刀具尺寸之间的函数关系。如图6(b)所示，实验采用M6刀具在1000 rpm转速下进行测试。

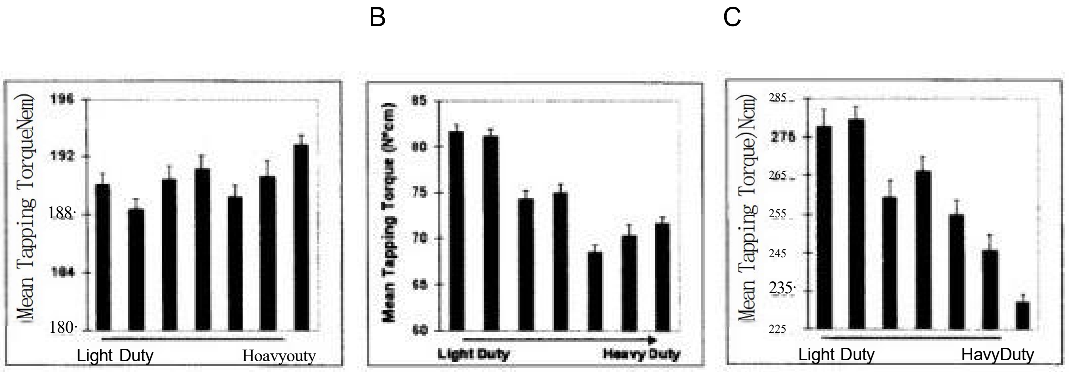

Fig. 7—Tapping torque results as a function of MWFs ranging from light to heavy duty. Tapping torque tests were performed at 1000 rpm with a)M6 TiN tools(resolving power =0.83),(b)M4 HSS tools(resolving power =3.96),and (c)M6 HSS tools(resolving power =23.14)of identical geometry.

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^3efficiencies 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).IfT^3experimental 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^3responses 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^3resolving power and expected field performance,a correlation coefficient(px,),for each operating condition was calculated as Eq.[6],

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

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.Sud duty and Sx 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 selectedT^3operating 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^3condition 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^3experimentation,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 416M4 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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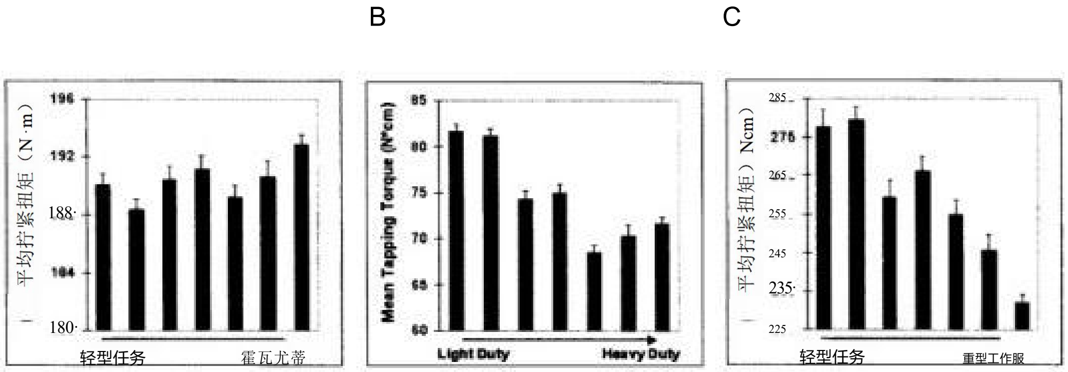

图7——轻载至重载条件下攻丝扭矩随MWFs变化的结果。攻丝扭矩测试在1000 rpm转速下进行，使用的工具包括：a）M6氮化钛工具（分辨力=0.83）、b）M4硬质合金工具（分辨力=3.96）以及c）几何结构相同的M6硬质合金工具（分辨力=23.14）。

对于HSS工具和1018冷轧钢工件而言，这些是最敏感的测试条件。在此情况下，分子项驱动了高分辨率值，导致不同流体间的T 3效率存在显著差异，其范围从去离子水的分辨率为约49%，可溶性油参考 MWF 可达91%（图4）。为覆盖预期 MWF 性能范围，实验采用了从去离子水到可溶性油的多种流体。这些流体被确立为标准流体组，用于计算分辨力。与 MWF 评估的所有环节一样，标准化处理对于确保分辨力指标的统一解读和比较至关重要。

抽油扭矩响应与现场性能的相关性

根据图6可以明显看出，运行条件既可以掩盖 MWF 性能（低分辨力），也可以提供区分 MWF 类型的方法（高分辨力）。如果选择分辨力较低的实验条件3，即使存在已知差异，也可能无法区分MWFs。为说明这一点，我们使用MES T 3对从轻载到重载的七种(7) MWFs进行了检测。MWF 额定值基于某大型 MWF 供应商的丰富现场经验。对于1000 rpm转速下的M6氮化钛工具，研究发现即使额定值最低的 MWF 也无法与额定值最高的 MWF 进行统计学区分（图7(a)）。然而当选择更高分辨力的工况（例如M4、HSS、1000 rpm）时，流体差异易于区分，且T 3响应与MWF 现场性能的预期趋势高度相关（图7(b)）。在最高分辨力的测试工况（M6、HSS、1000 rpm）下，预期现场性能被更清晰地捕捉到（图7(c)）。

为量化实验室T 3分辨力与预期场性能之间的关系，针对每种运行条件计算了相关系数（px），其计算公式为等式[6]。

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

分子表示流体负荷（按1至7的均匀比例缩放）与给定测试条件下平均抽油扭矩响应之间的协方差。Sud duty和Sx分别表示流体负荷与平均抽油扭矩响应的估计标准差。

表2中提供的相关系数表明所选T 3工况对预期现场性能的捕捉程度。相关系数清晰显示，随着分辨能力的提升，多波形滤波器（MWFs）的现场性能趋势预测效果更佳。由于较高的占空 MWF 应产生较低的抽头扭矩，理想情况下相关系数应为-1。当相关系数偏离-1较远时，说明分辨能力较低且 MWF 差异无统计学意义。因此可得出结论：分辨能力是量化T 3工况捕捉现场性能能力的有效指标。

解析能力与成本之间的权衡

显然，在以下两个方面之间存在权衡关系：1）减少T 3实验所需的时间、材料及成本；2）获取具有统计学意义的结果。因此，必须选择合适的测试条件，使扭矩测试能在最小重复次数下获得有效结果，从而降低成本。换言之，通过额外测试提高分辨率的经济效益必须得到充分论证。

本研究采用的实验装置中，工件成本约为150美元（无论是否预先钻孔并攻制240 M6孔或416 M4孔），工具费用根据涂层类型不同，M6规格工具成本为30-35美元，M4规格工具成本为25-30美元。基于上述数据，

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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 CONDrTION FOR THE DESIRED LEVEL OF CONFIDENCE (90%OR 95%), AND AsSOCIATED MATERIAL(ToOLAND WoRKPIECE) CoSTS.

TooL TYPE	TooL SIZE	STD. DEV.	N FROM EQ. [2] (90% CONFDENT)	CoST AT 90%	N FROM EQ. [2] (95% CONFDENT)	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^3has 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 improvedT^3resolution.Using ASTM D5619 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^3responses 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^3response to expected field performance increases.
- Designing T^3experiments 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.

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REFERENCES

(1)De Chiffre,L.and Belluco,W.(2000),"Comparison of Methods for Cutting Fluid Performance Testing,"Annals of the CIRP,49,1,pp 57-60.

(2)Upton,D.P.(1985),An Assessment of Cutting Fluid Performance *and Improvements in Surface Finish.*

(3)Werner,J.J.(1984),"A Practical Analysis of Cutting Fluids,"Lubr. Eng.,40,pp 234-238.

(4)Blanchard,P.M.and Syrett,R.J.(1974),"Mechanical Testing of Cutting Fluids,"Lubr.Eng.,30,pp 62-70.

(5)De Chiffre,L.(1980),"Mechanical Testing and Selection of Cutting Fluids,"Lubr.Eng.,36,pp 33-39.

(6)De Chiffre,L.,Lassen,S.,Pedersen,K.B.and Skade,S.(1994),"A Reaming Test for Cutting Fluid Evaluation,"Jour:of Synthetic *Lubrication,11,pp 17-34.*

(7)Lorenz,G.(1985),"Reliable Cutting Fluid Rating,"Annals of the *CIRP,34,1,pp 95-99.*

(8)Webb,T.H.and E.,et al.(1974),"Mechanical Testing of Cutting Fluids,"Lubr.Eng.,30,pp 315-321.

(9)Ladov,E.N.(1974),"A Tapping Test for Evaluating Cutting Fluids," *Lubr.Eng.,30,1,pp 5-9.*

(10)Belluco,W.and De Chiffre,L.(2001),"Testing of Vegetable-Based Cutting Fluids by Hole Making Operations,"Lubr.Eng.,pp 12-16.

11)ANSI (2000),ASTMD 5619:Standard Test Method for Comparing *Metal Removal Fluid Using the Tapping Torque Test Machine.*

(12)De Chiffre,L.(1978),"Testing the Overall Performance of Cutting Fluids,"Lubr.Eng.,34,5,pp 244-251.

(13)Mulberg,J.(2002),Introduction to Statistics,New York,Prentice Hall,p 157.

(14)DeVor,R.E.,Chang,T.-H.and Sutherland,J.W.(1991),Statistical *Quality Design and Control:Contemporary Concepts and Methods,* New York,Macmillan Publishing Company,p 809.

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表2——预期金属加工液场性能与1000 rpm转速下攻丝扭矩结果的相关性分析（采用相同几何结构的(a)M6锡合金、(b)M4高速钢及(c)M6高速钢刀具）

	职责	M6，TIN 1000 转/分钟	M6, HSS, 1000 转/分钟	M4, HSS, 1000 转/分钟	消解功率
M6，氮化钛，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

表3——在1000 rpm转速下，攻丝扭矩测试结果的标准差值随工具涂层类型及尺寸的变化关系

可溶性油参考液、为达到所需置信水平（90%或95%）而每个测试条件下所需的重复孔数，以及相关材料（工具与工件）

成本效益分析（CoSTS）

工具类型	工具尺寸	标准。偏差	N 来自公式[2]（90% 置 信度）	CoST AT 90%	N 来 自公式[2]（95% 置 信 区 间）	成本 95%	消解功率 (N=17)
氮化钛	M6	2.7	~19	$17.48	~30	$27.60	0.83
氮化钛	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

使用M4工具评估MWFs时，单次测试成本更具经济性——单个工件可进行近60%更多的测试，且每个M4孔的成本仅为0.54美元，而M6孔成本为0.92美元。尽管单次M4测试成本低于M6测试，但如表3所示，需进行更多重复测试才能达到同等置信水平。表3还表明，未涂层（高硬质合金） 工具具有更好的流体区分能力，但与其他涂层工具相比，需要更多重复实验才能达到特定置信区间尺寸。值得注意的是，最昂贵的测试条件（高硬质合金、M6 、1000转/分钟）提供了最高的分辨率能力，因此成为 MWF 评估中最敏感的T 3条件。虽然该结果支持通过经济投入提升数据质量，但必须承认：为 MWF 评估确定并应用高分辨率测试条件更具竞争力。另一种选择是进行大量T 3实验，但这些实验可能产生无法解读的数据，甚至导致误导性结果。

结论

传统的敲击扭矩测试（T 3方法已在多评估系统（MES） 背景下进行评估，即对单个工件进行多次测试。由于ASTM D 5619并非为MES设计，因此发现需要采用改进的 MWF 评估方法才能充分实现提高T 3分辨力的潜力。以ASTM D 5619为起点，建立了适用于MES的推荐实验考量因素。这些因素经过批判性分析后得出以下结论：

- 高性能工具会降低或消除 MWF 差异，这使得此类工具在评估 MWF 性能时效果不佳。除非工具涂层对 MWF 评估具有特定作用，否则不建议使用。仅在低磨损条件下于现场使用。
- 工具涂层的效果可能取决于工具尺寸。例如，未涂层的高速钢工具（HSS）在M4工具上的表现始终优于氮化钛工具，而氮化钛涂层在M6工具上的表现则始终更优。
- 针对最优性能的 MWF 选择不能仅基于单一条件下的T 3响应。关于流体性能的普遍结论，必须通过不同测试条件下的持续性性能结果才能得出。
- 分辨率指标被定义为量化衡量特定运行条件区分多波形信号（MWFs）能力的指标 。随着分辨率提升 ，T 3 响应与预期场性能之间的相关性也会增强。
- 基于最小化单次测试成本来设计T 3实验，可能导致对制造条件下MWFs潜在功能性的判断存在偏差或误导性结论。扭矩测试实验必须经过系统化、有计划地设计，以最大化每次测试的战略价值。

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参考文献

(1) DeChiffre，L. 与Belluco，W.（2000 年）《切割液性能测试方法比较》，载于《 CIRP 年鉴》第49卷第1期，第57-60页。

(2) Upton,D.P.(1985年),切削液性能评估*与表面光洁度改进.*

(3) Werner，J.J.（1984），“切削液的实用分析”，《润滑工程》，第40卷，第234-238页。

(4) Blanchard，P.M. 与 Syrett，R.J. (1974)，《切削液力学测试》，《润滑工程》，30卷，第62-70页。

(5) De Chiffre，L.(1980)，“切削液的力学测试与选型”，《润滑工程》，36卷，第33-39页。

(6) De Chiffre，L.、Lassen，S.、Pedersen，K.B. 与 Skade，S.（1994年），“切削液评估的扩孔试验”，《合成*润滑学杂志》，第11卷，第17-34页。*

(7) Lorenz，G.(1985年)，“可靠的切削液等级评定”，《*CIRP 年鉴》，34卷第1期，第95-99页。*

(8) Webb，T.H. 与 E. 等（1974），“切削液的力学测试”，《润滑工程》，第30卷，第315-321页。

(9) Ladov，E.N.（1974），“一种用于评估切削液的敲击试验”，*《润滑工程》，30卷第1期，第5-9页。*

(10) Belluco，W. 和 De Chiffre，L. (2001)，“通过打孔操作测试植物基切削液”，润滑工程，第12-16页。

11) ANSI（2000）， ASTMD 5619：采用扭矩测试机比较金属去除液的标准测试方法。

(12) De Chiffre，L.（1978），“切削液整体性能测试”，《润滑工程》，34卷第5期，第244-251页。

(13) Mulberg,J.(2002年),《统计学导论》,纽约:普伦蒂斯霍尔出版社,第157页.

(14) DeVor，R.E.、Chang，T.-H. 及 Sutherland,J.W.(1991),《统计*质量设计与控制:当代概念与方法》*,纽约,麦克米伦出版公司,第809页.