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Improved examination and test procedure of tapping torque tests according to ASTM D5619 using coated forming taps and water-mixed metalworking fluids

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Abstract

Tapping torque test is a standardized (ASTM D5619-00) approach evaluating the lubricity of metalworking fluids. It was detected that running-in behaviors of taps and carryover effects caused by previously used fluids were not investigated. Further, it is detected that effects due to changed tap conditions or fluids are underestimated. The low number of measurements leads to deviations of torque means. In this contribution, the running-in phase of coated forming taps is evaluated by measuring tapping torque in AlMgSi1, C45E, and AlSi7Mg materials using water-mixed metalworking fluids.

New tests and calculation methods considering tool wear are suggested. As outcome increased experimental significance at higher confidence levels, comparability between taps and test platforms, and better distinguishability of water-mixed metalworking fluids are obtained.

Keywords: Running-in, Emulsions, Forces, Lubrication

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1. Introduction

The use of metalworking fluids in industrial machining processes is widely spread. The fluids cool and lubricate the contact zone between tool and workpiece to prevent tool wear and to ensure manufacturing of required geometries and surface qualities. To recommend the best suitable metalworking fluid for each machining process, lubricant manufacturers use empirical data of similar applications as well as results from standard laboratory wear tests e.g. Reichert and Brugger test or cutting force tests e.g. tapping torque test. In comparison to cutting force tests in drilling, turning, or reaming operations, tapping tests show the best relative resolution related to special cutting fluids and work materials [1]. Lubrication reduces friction between tool and workpiece and can increase surface quality and tool life time. A general statement is not possible and the machining result depends on the effects of the fluid's contents. The type of fluid and its contents/additives mainly affect tool wear and surface roughness or make higher machining speeds possible to decrease manufacturing time and increase the output. Apart from good lubricating and

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cooling properties, other properties such as corrosion inhibition, flushing and defoaming properties, long-term stability, skin and environmental compatibility can also be included in fluid requirements.

Most of these established tests are performed strongly related to conformed standards and rules of relevant institutions e.g. the DIN (German Institute for Standardization) or German VKIS (Consumer network industrial lubricants). The relevant regulation for the tapping torque test is ASTM D5619-00 (2011), *Standard Test Method for Comparing Metal Removal Fluids Using the Tapping Torque Test Machine* standardized by ASTM International (American Society for Testing and Materials). The last active version of ASTM D5619-00 (2011) has been withdrawn in 2016 with no replacement. Due to missing alternative it can be assumed that the last version is still widely used to evaluate the performance of metalworking fluids. The present contribution highlights the problems of the withdrawn standard and proposes changes to improve test conduction, evaluation, and significance of test results for a new version and therefore provides the fundamentals for an alternative.

The introduction is divided into three subsections. In the first subsection, key points of the recent standard are described so that the reader is able to understand the consequences of existing definitions and the lack of necessary definitions. In the second subsection, literature is reviewed with respect to contributions applying this standard or a modified version. Here, articles are focused using tapping torque as a measure to evaluate the functionality of tool coatings, effect of different pre-hole diameters, or other test related parameters. To highlight the necessity for improvements of the withdrawn standard, the problems are summarized in a critical evaluation in the third subsection.

1.1. Key points of ASTM D5619

The tapping torque test is described as more accurate than previously available laboratory scale tests to predict the performance of metalworking fluids [2]. The aim is to find the best suitable fluid for a specific application i.e. a specific material pair combination. Threads are cut by taps into pre-drilled and pre-reamed holes while lubricating the contact zone between tap and hole wall by a metalworking fluid. The required torque to cut a thread is recorded and serves as the main feature to evaluate the test fluid in comparison to a reference fluid. As defined in ASTM D5619, only measurement values from the plateau region (Figure 1) of each thread have to be taken into account for mean calculation. The lower the tapping torque mean, the higher the test fluid's lubricity for the tested material pair combination.

The final resulting characteristic value of a test fluid is the tapping torque efficiency TTT_{eff} describing the quotient of reference fluid and test fluid as [2]

$$TTT_{eff}[\%] = 100 \times M_{ref} \,/\, M_{test} \,, \tag{1}$$

with M_{ref} denoting the mean of the reference condition and M_{test} the mean of the test condition.

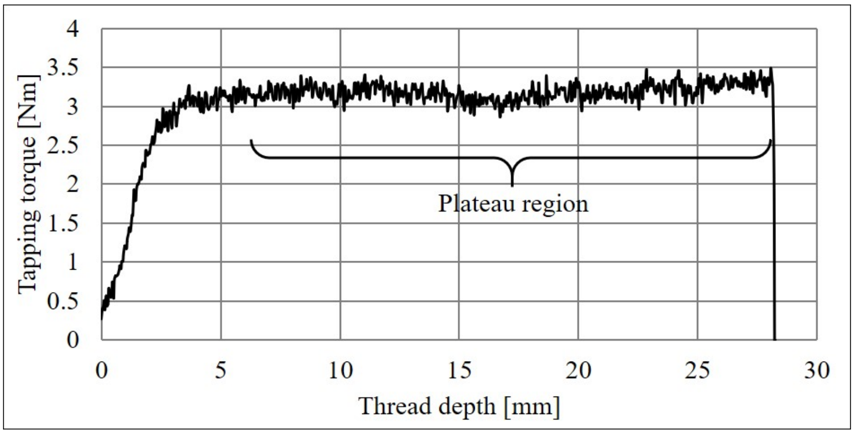

Figure 1: Plateau region of an exemplary torque measurement in AlMgSi1. The mean is calculated from 6 to 27 mm.

Different taps and different workpiece materials can be used for tapping torque tests. Each material pair combination can result in another best suitable metalworking fluid. Test results strongly depend on the chosen experimental design. To achieve results with best significance and best transferability into practice, it is recommended to use the same material pair combination in the tapping torque test as it is used in the real application [3]. To exploit this main advantage of high flexibility of tapping torque tests, workpiece and cutting materials are not bindingly defined in ASTM D5619 as well as machining speeds and fluid types.

The ASTM D5619 prescribes a running-in and a qualification process for the taps to be used for tapping torque tests. New taps have to finish their running-in phase first, then to be checked as qualified before using them for tapping torque tests [2]. The necessity to run-in new taps is established to achieve characteristic built-up edges on the tap. The term *built-up edge* is given by ASTM to describe a characteristic wear state of the used tap. These specific built-up edges are built on the cutting edges of the tap and belong to the chosen test condition of tap and workpiece material, fluid, and machining speed. How these built-up edges should be examined (microscopic wear images, torque, or...) to obtain equal initial conditions is not described in ASTM D5619.

The test conditions of running-in are also not defined. It has to be assumed that they match with those of the tap qualification process directly following the running-in. Thus, the running-in of the tap would simultaneous be the qualification process. The tap qualification is recommended to be performed in a 1215 steel alloy - regardless in which material the test run later will be performed. The built-up edge on the tap will be characteristic for cutting 1215 steel alloy using the reference fluid. The fluid to be chosen as reference fluid should not contain surface activating additives and should produce minimal built-up edges [2].

In the tap qualification process, five threads are performed. The standard deviation is calculated according to the usual formula as

$$stdd_{\overline{x}} = \sqrt{\frac{\sum(x-\overline{x})^2}{(n-1)}}\ , \tag{2}$$

with x denoting a single measurement value, $\overline{x}$ the sample mean, and n the sample size.

The allowed standard deviation of the mean of each tap is ± 2 %. The allowed difference between the mean of the reference tap and the mean of another tap is ± 2 %. Concluding, the mean of the other tap has to lie in between the lower and upper 2 % bounds of the reference tap. Taps not fitting into this requirement have to be discarded leading to high test effort and high tool costs.

After running-in and tap qualification, the test sequence can begin. At this point, it is unclear if the reference fluid should be used in the same workpiece material before using the test fluid or if the reference fluid is only tested in 1215 steel. It is also not defined if regular reference measurements shall be performed between test runs to monitor proceeding tool wear.

The test fluid is measured for five threads. To calculate the test fluid's mean, only values of the last three threads are taken into account [2]. Possible carryover effects of the previously used fluid are so taken into account by two threads. Reducing the amount of values contributing to the mean implies a higher standard deviation and worse statistical differentiability between test fluids.

1.2. Literature review

Threads can be realized in two different ways: Cut tapping or form tapping. The diameter of the pre-holes for cut tapping is smaller than that for form tapping because excess material is cut away by the cutting edges of the tap to build the final thread. In form tapping the existing material is elastically and plastically deformed by the lobes of the tap. Tools for cut tapping have flutes for chip transportation. Tools for form tapping can have oil grooves for lubricating aspects. In this case, the forming lobe is located just between the grooves. The fundamental processes of cut and form tapping processes differ strongly [4, 5] and are not focused in this article. Cut tapping is the less reliable process for tapping torque tests because chip curls can drag and jam in the tap's flute and can contribute to the measured tapping torque. Thus, the ASTM D5619 is not only realized and applied for cut tapping but also for form tapping. In the experimental part of this article, tests are conducted in form tapping.

In the present contribution, the fundamental processing of cut and/or form tapping is not focused. Here, the methodology of performing and evaluating tapping tests is discussed in general. The literature review contains contributions dealing with cut or form tapping. The contributions are analyzed regarding test procedure, reference measurements, start parameters/running-in of tools, tool qualification processes, considering of carryover effects, number of replicates and test deviations. The result evaluations of these contributions are investigated due to differences between test fluids and statistical evaluations. These criteria are important for tests using cut taps as well as form taps.

In literature, many contributions have dealt with tapping torque tests or tapping processes. Most of the tapping torque tests were performed according to ASTM D5619 [4, 6, 7] or to a modified, similar procedure. Uncoated or coated tools with diameters between M4 and M10 were used in thread cutting and thread forming operations in workpiece materials reaching from carbon steels to highly alloyed steels or various aluminum alloys. The effect of different fluids i.e. base oils, additives on the tapping torque [8, 9, 4, 6, 10, 11] and of different tool geometries [12] was investigated. Exemplary, a less effective oil needs a 53 % higher torque than a highly effective oil in form tapping of hardened steel [10]. Tool coatings have a significant effect on tapping torque and tool wear [9, 13, 5, 14, 15] and on thread surface quality [14]. Lubricants not only influence the tapping torque but can also affect the micro-hardness of the flank of the formed thread [16]. Pre-hole diameters and forming speeds influence the tapping torque [7].

The usability of tapping torque and reaming torque tests for cutting fluid evaluation were investigated. By comparing both tests, reaming torque tests were evaluated to be a viable alternative to tapping torque tests [17]. Different machining methods were tested to evaluate cutting fluid efficiencies [18, 19]. Laboratory lubrication tests were compared with real manufacturing processes: Brugger and tapping torque tests were performed using non-water miscible metalworking fluids with different additive combinations. A transferability of both tests to industrial forming processes was proven using the same workpiece and tool material combination [3]. A good correlation between measurements of tapping torque tests with high resolving power and field performance were obtained using the same fluids [15].

The running-in behavior of tapping tools to be used for tapping torque tests has rarely been investigated. For dry tapping and tapping with minimum quantity lubricant without additives, a running-in behavior of the used cutting taps can be recognized [9]. It can be concluded that the running-in effect is not recognizable for higher lubricating conditions with flooded tap oil or minimum quantity lubricant containing additives. The running-in phase is possibly affected by the lubricating ability of the used fluid.

The necessity to run-in the taps before starting the test sequence is mentioned in several contributions. Details about the number of threads or the tolerated deviation of the means are often not given. The importance of repeating reference measurements after the running-in is emphasized to verify that tool wear has no effect on the measured tapping torque [15]. The tolerated deviation from the reference value is not mentioned and the repeated reference values are not taken into account in the calculation of tapping torque efficiency.

Before conducting the lubricant's test, the forming taps are firstly used with the reference fluid [4]. It is not mentioned for how many threads the reference fluid is used but the measurement values are also used to qualify the taps. Taps with a *repeatability* of 2 % are qualified [4]. The equation to determine the repeatability is not given.

In a few contributions [3, 20, 21], the test procedure is considered in more detail. Good repeatability and reproducibility of tapping torque tests are obtained applying a suitable order of test sequence for the fluids [20, 21]. Regular reference measurements are performed [3, 20, 21] to monitor the effect of tap wear. In most cases, the changed reference values are not integrated in the calculations of tapping torque efficiencies. Reference values can change up to 12 % when using new forming taps of the same batch [4]. To be able to compare the measurement values of different taps, a *coefficient of correction* is introduced. Although the calculation of this coefficient is not described, it is used to calculate an *average tapping torque corrected* [4]. The corrected values are used to directly compare the test results of fluids obtained with different forming taps.

Multiple tapping torque testbeds are proposed to increase the sensitivity of tapping torque tests [15]. The importance of selecting suitable test conditions to be able to distinguish between metalworking fluids is also emphasized. Differences between measurement results are analyzed using a statistical significance test (t-test) assuming a normal distribution for the plateau area of the torque curve. As a result, it is stated that tool coatings, tool sizes, and machining speeds significantly affect the resolving power of the tests [15]. Four different tap coatings and four different fluids were evaluated in tapping of carbon steel (SAE 1018) at 500 and 1000 rpm. Coated high performing tools were found to be ineffective for metalworking fluid examination because of very small and not statistically significant differences between test fluids [15]. The highest resolving power was gained with an uncoated M6 high speed steel tap at 1000 rpm [15]. A minimum number of replicates of each test condition has been determined to allow statistically distinguishable values for the test fluids [15]. Based on experimental experience, 20 to 30 replicates are proposed depending on the resolving power of the chosen test conditions.

Fluid type, tool coatings, workpiece to workpiece variation, and tool to tool variation have statistical significance on the measurement results [15]. Tool to tool variation is discussed to have less effect on the results than the other three parameters. That means the allowed standard deviation of ± 2 % between tools defined in ASTM D5619 is surpassed by fluid type, tool coating, and workpiece variation [15]. In another contribution, the differences between the taps are evaluated as so significant that a correction coefficient is applied to compensate the differences between the taps [4].

To the knowledge of the authors, no contribution is known investigating carryover effects by previously used fluids on tapping torque test results. In some articles [4, 3], the test procedure is described in such a way that the conditions before starting a test run are adapted. A reference fluid is used for one thread to set the same starting conditions before changing the fluid and to monitor a drift of the measurement values [3]. An influence of the previously measured fluid is assumed to be significant but it is not investigated further. A comparison between measurements with and without this initial condition is not made. In another contribution, each tap is only used for the reference fluid and for one lubricant to strictly avoid contamination effects [4].

Summarizing the literature review, a transferability into field application has been shown for tapping torque tests. The necessity of regular reference measurements or the significance of carryover effects has not been investigated in detail. The strong difference between initial values of taps has been considered only in one case by introducing a correction coefficient. Details about measurement deviations are often missing and measurement results have been statistically analyzed only in few cases. No contribution can be found considering the definition of the initial test condition or dealing with the investigation of the characteristic built-up edge to precisely define the end of running-in phase of a tap. Therefore, suitable measurement methods or useful features have not been discussed.

1.3. Critical evaluation

This contribution focuses on a critical evaluation of the conduction and evaluation of tapping torque tests exclusively according to [2]. The ASTM D5619 provides many opportunities to choose different workpiece materials, reference fluids, or manufacturers for tapping tools. Recommendations for suitable reference fluids and the number of replicates are given. A tap qualification process (2 % deviation) and an initial criterion (built-up edge) are defined. Evaluation criteria for the built-up edge are not detailed. Based on experimental experience, questions concerning the test conduction and some problems with definitions of ASTM D5619 appear. These are not clearly defined and should be more detailed to obtain unambiguous and repeatable test results. The following points need to be improved:

1. The completion of a running-in phase is required before starting tests with new taps. The running-in phase is finished when a characteristic built-up edge has been built belonging to the specific type of tool and the specific fluid used for running-in. Technical utilities to be used to evaluate built-up edges (optical microscope for wear inspection, tapping torque tester for torque monitoring) are not described. A systematic procedure to clearly identify the end of running-in of a new tap is not explained.
2. For tap qualification, the use of a SAE 1215 carbon steel alloy is recommended. Although the test method allows tests on other workpiece materials, the taps should all be qualified on the same workpiece material. It should be noted that not every tool has been developed for machining of SAE 1215 steel and is possibly not suitable for this material. The workpiece material could cause premature tool damage or the tool would even get stuck in the thread. As consequence, misleading conclusions may occur when using workpiece materials not recommended by tool manufacturers.
3. For qualified taps, a 2 % deviation of the means is allowed. This feature has to be checked only during the tap qualification procedure by using the reference fluid. Over the whole life of the tap, wear proceeds and the tap possibly does not fulfill the qualification definition further. Regular reference measurements to monitor the tool's condition are not recommended. A criteria for the end of tool life is not defined.
4. Taps not fulfilling the recommended 2 % deviation are not qualified for tapping torque tests and have to be sorted out into appropriate qualified groups. Taps within one group are comparable with each other. Taps between groups are not comparable with each other. This recommendation increases experimental costs because many taps are needed.
5. A strong effect of the workpiece material's quality on the measurement results is described. A procedure to qualify test platforms is not proposed. The material composition of test platforms may significantly affect repeatability and comparability of measurement results. This makes the development of a data base containing directly comparable tapping torque test results impossible. A reference value valid for a specific material pair combination is missing that could be used to normalize mean torques and to ensure comparability of test data.

6. Neither a special tool type or tool coating nor a geometry of flutes/grooves and edges are recommended. Uncoated tools have higher resolving power than coated tools so fluids can more often be distinguished using uncoated tools than using coated tools [15]. High performance coatings can also mask the fluid's performance so that uncoated tools seems more suitable than coated tools. The aim of tapping torque tests is to replicate field conditions as good as possible. Coated tools are used in field applications. Using only uncoated tools reduces the transferability into practice.
7. The number of threads per fluid is set to five. For the test run, the mean torques of the first two threads are not included in the calculation of the overall fluid's mean. The fluid's mean and its standard deviation are based on three measurements. This small number of measurements leads to high standard deviations, wide confidence intervals, and finally to non-suitable differentiability of test fluids.
8. Carryover effects of previously measured fluids can affect the following test run. By taking these effects into account, the first two of five single measurements are discarded and the mean torque is calculated for the last three measurements. Depending on reactions of the previously measured fluid with the tool's surface, two threads could be insufficient to eliminate carryover effects, especially when thread depth is not defined.

As illustrated, several problems with the current test procedure occur based on reasonable considerations as well as on practical experiences. The existing regulations lead to high tooling costs, not clearly defined initial test conditions, bad comparability between test fluids over the whole tap life, possible not significant differentiability between test fluids, and less transferability into practice. These points could be avoided or significantly improved.
In this contribution, first experimental results of tapping torque tests are presented and statistically validated. The aim is not to find a best suitable fluid for a specific application but to improve the standard's test procedure and the evaluation of test results. Second, suggestions are developed to overcome problems due to quality differences of taps, proceeding wear, fluid carryover effects, and statistical significance of test results. Third, comparisons based on statistical tests are made between the recent regulation and two new approaches to show the effectiveness of the suggested changes.

2. Experimental procedure

The experimental test rig partly shown in Figure 2a consists of a tribometer (Tauro®120, Taurox e. K., Germany), test platform, tapping tool for thread forming, different test fluids, and a cleaning station with brushes and air blow system to remove chips and fluid residues. In the present tests, no rigid tapping is used. The spindle is fixed at a weight compensated suspension. During threading, the spindle is turned into the nut blank through the thread flanks of the tap. The axial force only works at the entry taper until the first thread flanks have caught material. In Table 1, materials and test parameters are listed. The displayed forming speeds are recommended by the tool manufacturer for his tap and the concerned workpiece material.

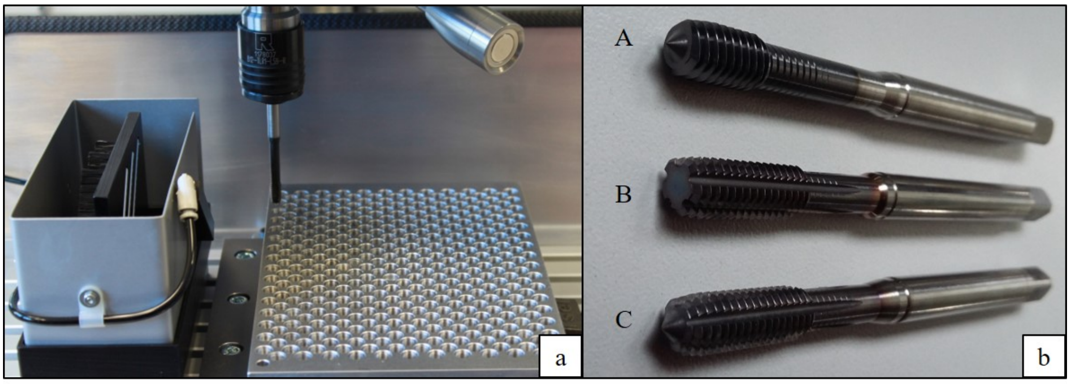

Figure 2: a: Tapping machine, tapping tool, pre-drilled test platform and cleaning station of the tribometer used for tapping torque tests (Rhenus Lub, Germany). b: Different tapping tools for thread forming used in the tests

Table 1: Used test materials and parameters for tapping torque test conduction and evaluation

Parameter	**AlMgSi1**	**C45E**	**AlSi7Mg**
Hole diameter [mm]	5.6 H7	5.6 H7	5.6 H7
Hole depth [mm]	31.3	31.3	26.5
Forming speed [m/min]	25	20	20
Water for emulsions	Deionized	water	
Fluid volume per thread [ml]	≈ 0.8	≈ 0.8	≈ 0.6
Tapping depth [mm]	27.3	27.3	24.3
Evaluated thread length [mm]	6-27	6-27	4-24
Sample rate [Hz]	500	500	500

Although fluids could be easier distinguished using uncoated tools in tapping torque tests [15], coated tools are chosen for the experiments (Table 2, Figure 2b). In practice, coated tools are often preferred because higher speeds and longer tool life can be achieved. Uncoated tools lead to early tool failure in comparison to coated tools [14]. Another disadvantage of uncoated tools is that they may entail higher material adhesion and wear. The use of uncoated tools can lead to a shortened steady-state wear phase in comparison to coated tools. Less test measurements could be performed with one tool leading to a higher number of tools to be acquired and qualified. In this contribution, tapping of AlMgSi1, C45E, and AlSi7Mg is investigated. It is assumed that the micro-structure of these materials complies with those of standard applications and is homogenous. Similar alloys have been tapped in other researches [9, 14, 22, 23, 24].

The contents of the used workpiece materials are listed in Table 3. Each test platform has pre-drilled and pre-reamed holes with 5.6 H7 mm diameter suitable for M6 forming taps. Platforms made of AlMgSi1 and C45E have 368 holes in 23 columns of 16 holes and platforms made of AlSi7Mg have 112 holes in 8 columns of 14 holes. The machining

Table 2: Characteristics of forming taps made acc. to DIN 371, form C and DIN 2174

Tap	**Specification**
A	Without grooves, entry taper 3 pitches, 10 mm thread length, 4-polygon form, HSS-E, multi layer coated, M6
B	Five grooves, entry taper 3 pitches, 17 mm thread length, 5-polygon form, HSS-E-PM, TiCN coated, M6
C	Five grooves, entry taper 3 pitches, 17 mm thread length, 5-polygon form, HSS-E, TiCN coated, M6

Table 3: Alloying elements of the used workpiece materials in %

Alloy	**C**	**Si**	**Mn**	**P**	**S**	**Cr**	**Ni**	**Cu**
C45E	0.444	0.232	0.683	0.014	0.005	0.016	0.005	0.008
	Al	**Nb**	**Mo**	**V**	**Ti**			
C45E	0.03	0.002	0.001	0.001	0.001			
	Si	**Fe**	**Cu**	**Mn**	**Mg**	**Cr**	**Zn**	**Ti**
AlMgSi1	1.2	0.16	0.07	0.63	0.7	0.01	0.01	0.01
AlSi7Mg	7.0	0.45	0.15	0.35	0.5	-	0.15	0.2
	Sn	**Ni**	**Pb**					
AlSi7Mg	0.05	0.15	0.15					

table of the tribometer is programmed in such a way that the threads are machined column by column from back to front.

The pre-hole diameter has a significant impact on tapping torque and thread geometry [14, 25]. It is assumed that the given H7 tolerance ensures a comparability between the holes and hence between the test results. Before testing, the holes are proven by a GO/NO GO pin gauge. The maximum thread depth of the forming process is limited either by the depth of the pre-hole (AlSi7Mg) or by the length of the tapping tool up to its wider shaft (AlMgSi1, C45E). Before testing, platforms are cleaned in an ultrasonic bath for 15 min. using a cleaning solvent (1:1 mixture of naphta and isopropyl alcohol) and dried in a drying oven at 50 °C for 15 min. New taps are cleaned by repeated washing and wiping steps using the same solvent mixture before using them for the first thread.

Due to the automatic program of the tribometer, the tap is automatically cleaned in the cleaning station after every thread before the tapping process proceeds with the next hole. To determine the mean of a single thread, the plateau region (Figure 1) of the torque curve is chosen [2, 15, 10]. The values of the single measurement curves are not filtered or smoothed as can be seen in Figure 1. Mean and standard deviation of a single thread (Equation 2) are calculated by the software of the tribometer according to the chosen definition range. Details about the used materials and fluids used are given in the diagrams and figure captions.

3. Results

The results are divided into three main parts. In the first part, the running-in behavior of two differently coated tapping tools is discussed. In the second part, the importance of regular reference measurements is shown. The third part deals with different examination methods with respect to the significance of measurement results and conclusions concerning carryover effects.

3.1. Running-in

According to ASTM D5619, a cutting tap is finally broken-in when a characteristic built-up edge has been formed by cutting threads using a reference fluid. The present article deals with form tapping and the authors found that the appropriate term to *built-up edge* is *adhered layer* on the forming lobes. This term does not specify if hard material or a chemical layer has occurred.The term *a broken-in tap* means that the tap has finished its running-in phase. After the tap is broken-in, a nearly stationary phase follows in which wear and resulting mean torque are quasi constant. The evaluation of built-up edges requires special equipment such as magnifiers or microscopes and high expertise by the operator. To continuously control the edges consumes time and increases measurement costs. To facilitate the determination of a broken-in tap, it is proposed to use the same features as are already used for the final test procedure i.e. mean torques. Derived from the specific order of pre-holes on the test platform (, k number of holes per column), the following criterion for a broken-in tap at thread number i is proposed by the authors

$$|M_{i+k-1} - M_i| < stdd_{M_i} \ , \tag{3}$$

with M_i denoting the torque for thread number i, k the number of threads per series (k=16 for AlMgSi1 and C45E), and $stdd_{M_i}$ the standard deviation of the mean torque of thread number i. In the stationary phase, single outliers are tolerated.

The criterion is used to characterize the end of running-in phases of taps. The fulfillment of this criterion is exemplary shown for taps A-9 and B-4 in Figure 3a. For tap A-9, the criterion is fulfilled beginning from thread number 15. For tap B-4, Equation 3 is always fulfilled. The authors assume that tap type B shows a shorter running-in phase because of higher production accuracy or additional downstream production steps.

In Figure 3b, Equation 3 is applied to the measurement values of every tap to find the end of their running-in phases. Thread numbers fulfilling Equation 3 for the first time are marked by black boxes. Different lengths of running-in phases are observed for taps of type A: The running-in ends between thread no. 7 and 22. A correlation between k-value and the length of running-in phase can not be recognized. A conclusion if the fluid affects the running-in behavior can not be drawn from Figure 3b. As a consequence, the need for a running-in and the length of the running-in depends on the tap and has to be investigated in each specific case before performing tapping torque tests.

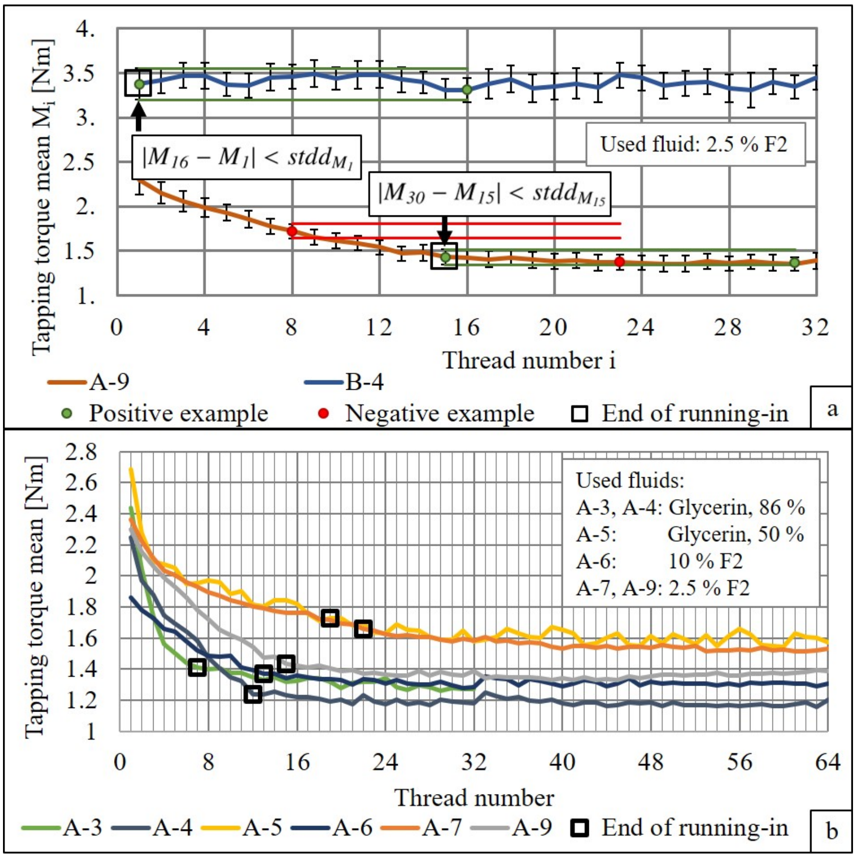

Figure 3: a: Running-in behavior of two different tap types in AlMgSi1. The running-in criterion defined by Equation 3 is applied to the means and standard deviations. Tap B-4 has no running-in phase. The running-in phase of tap A-9 is 14 threads. b: Determination of broken-in taps by mean torques. Tapping tests are performed in AlMgSi1. The running-in criterion defined by Equation 3 is applied to the means and standard deviations of six taps. The first thread of each tap fulfilling the criterion is highlighted by a square.

3.1.1. Type of tool

Subsequently, the running-in behavior of two different tapping tools is exemplary investigated. In Figure 4a, the mean torques of the first 32 threads of tap types A and B in AlMgSi1 are shown. Taps A-1, A-2, and A-3 as well as taps A-7 and A-9 as well as taps B-2, B-3, and B-4 are used on the same test platforms and with the same fluids so a comparison between tools of the same group is possible.

The mean torques of tap type A start at around 2.4 Nm. Increasing the thread number leads to a decreasing tapping torque until a steady-state is reached. A running-in process can be detected. Taps of type B generally need a higher torque for the threading process than taps of type A. For tap type B, a running-in phase cannot be detected.

The strong impact of the tap type on the torque level can also be recognized by comparing measurements of A-7 with A-9 (dotted lines) and taps of type B with each other (Figure 4a). The slope of the mean torque can vary although the same tap type and the same fluid are used.

The example depicted in Figure 4a can also be used to explain tap qualification. The tap qualification process

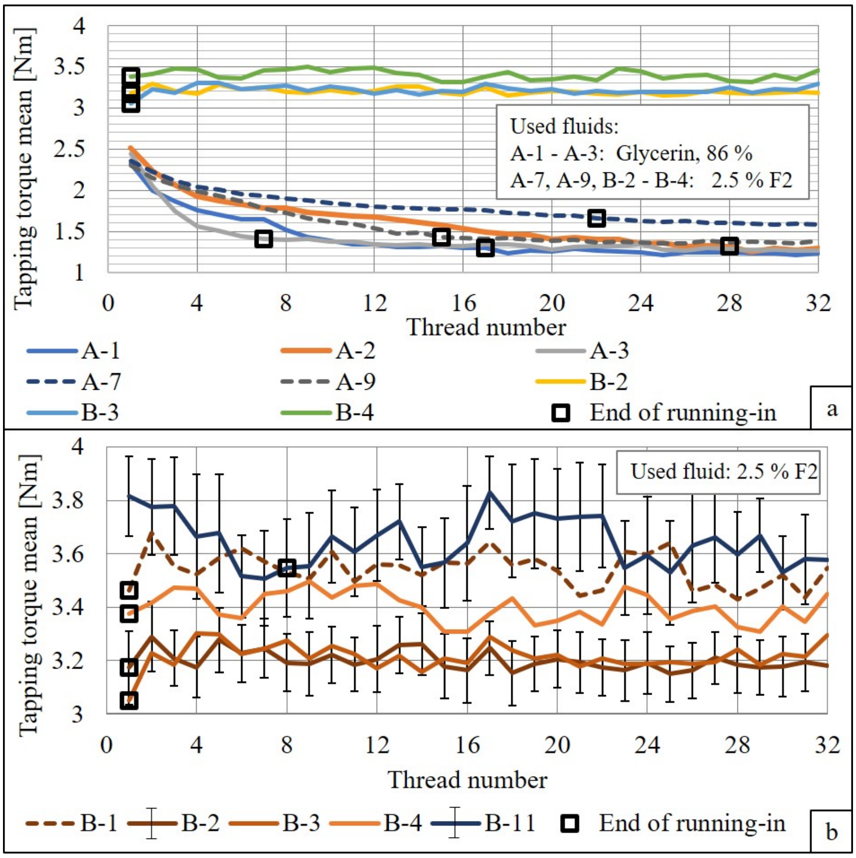

Figure 4: a: Running-in behavior of different taps in AlMgSi1. For same test conditions different running-in behaviors can be detected varying from tap to tap. b: Comparison of running-in phases of tap type B in AlMgSi1 (B-1 to B-4) and C45E (B-11). Similar mean torques are achieved for both materials.

prescribes a maximum allowed deviation of 2 % between taps. The allowed 2 % tolerance range is applied to taps of type A and B and are listed in Table 4.

Taps A-1, A-2 and A-3 are in one group, A-7 and A-9, and B-2, B-3, and B-4. For each reference tap, lower and upper bound are noted. By comparing the means with the lower and upper bound of the reference tap, it is checked if the means are within the range. Tap A-1 is within the range of A-2 and a qualified tap. Tap A-3 is out of the range of A-2 and is evaluated as disqualified. The mean of A-9 is out of the range of A-7. Taps B-3 and B-4 are out of the range of B-2. Following the criterion for tap qualification defined by ASTM D5619, only one tap would be qualified and four of eight taps of three different groups have to be discarded. Therefore, the defined 2 % range has a strong impact on experimental costs. Quantifying torque tolerances for each tap type and conducting significance tests to statistically evaluate the differences between taps could be more economic than testing a very high number of taps. Changing the equation of tapping torque efficiency (Equation 5) would also be efficient by implementing a normalization factor that is calculated from means obtained during tap qualification. An equation for this purpose is introduced in Section 3.2.

Table 4: Applying the 2 % tolerance range for tap qualification. For compared taps in one group the same reference fluid was used.

Tap	Mean [Nm]	Lower 2 % bound [Nm]	Upper 2 % bound [Nm]
A-1	1.296	qualified	
A-2	1.317	1.291	1.343
A-3	1.408	disqualified	
A-7	1.658	1.628	1.691
A-9	1.433	disqualified	
B-2	3.173	3.110	3.236
B-3	3.049	disqualified	
B-4	3.376	disqualified	

3.1.2. Workpiece material

From Figure 4b, conclusions can be drawn regarding the effect of two different workpiece materials on the tapping torque level. The effect of workpiece material on the running-in behavior has been investigated for tap type B. Taps B-1 to B-4 are used in AlMgSi1 and tap B-11 in C45E. Taps B-1 to B-4 are broken-in from the first thread on whereas B-11 is broken-in after eight threads. The workpiece material may significantly affect the running-in phase of a tap.

Tap B-1 (dotted line) was used in another platform than taps B-2, B-3, and B-4. The torque level of B-1 is higher than those of B-2 to B-4 so an effect of platforms of the same workpiece material can also be assumed. Summarizing, different platforms of the same material can influence the level of mean torque and the workpiece material can affect the running-in phase of the taps.

3.2. Reference measurements

The test procedure of ASTM D5619 does neither consider nor recommend regular reference measurements. Regular reference measurements will be important if one tap is used for many test series with different metalworking fluids and/or on different test platforms. The introduction of a theoretical reference value at test series no. i will be the basic of comparable measurement values when performing many test series with the same tap. To show the importance and necessity of regular reference measurements, experimental tests are performed (Figure 5). Taps A-10 to A-13 are used in AlMgSi1 platforms to investigate the development of reference measurements up to 288 threads. After tap's running-in, the reference values slightly increase. Exemplary, for tap A-11 the reference value starts at about 1.7 Nm (thread no. 64), increases steadily and exceeds 2.0 Nm at thread no. 264. Applying Equation 1 to a fictitious test mean of 1.9 Nm, the tapping torque efficiency could vary between 89 % (1.7 Nm as reference value) and 105 % (2.0 Nm as reference value). For correct efficiency calculations, the operator has to know the recent

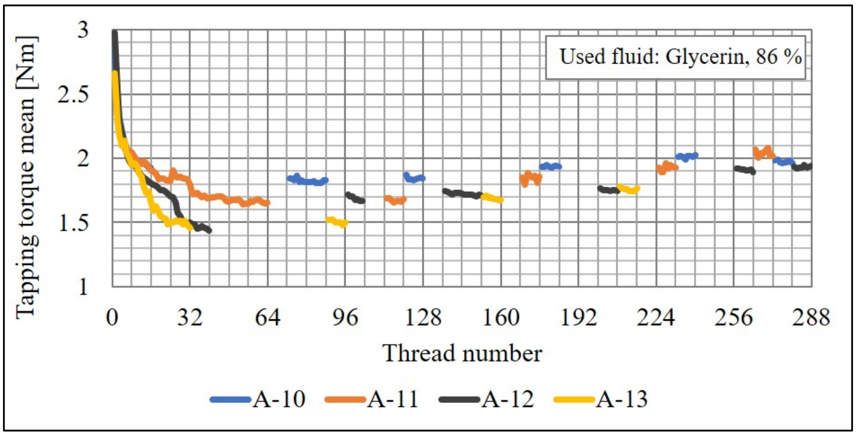

Figure 5: Regular reference measurements in AlMgSi1 for checking and monitoring the reference value. Over tool life, the reference value changes significantly. Consideration is important for calculation of tapping torque efficiencies.

reference value corresponding to the recent test measurement. As a consequence, not checking the reference value in regular measurements could result in wrong test results and misinterpretations.

A verification of the reference value before and after each test measurement, would lead to immense experimental effort and costs. To get a sufficient approximation to a real reference value, the following procedure is proposed: Performing reference measurements before and latest after every sixth test run. This means after the first/beginning reference series, up to six test series are performed. The seventh series is again a reference series. From each series, a mean is calculated representing the measurement value of each series. Between the beginning and end reference value, a linear slope is assumed so that a linear interpolation between these values is used to established a corresponding theoretical reference value of each test measurement. This theoretical reference value is introduced to deal with tap wear over the whole life of the tap.

The theoretical mean reference is calculated as

$$M_{ref,i} = M_{ref,\alpha} + (M_{ref,\omega}\text{-}M_{ref,\alpha}) \times (z_i\text{-}z_\alpha) \;/\; (z_\omega\text{-}z_\alpha)\ , \tag{4}$$

with $M_{ref,i}$ denoting the theoretical mean reference at test series no. i, $M_{ref,\alpha}$ the measured mean reference before the test series, $M_{ref,\omega}$ the measured mean reference after the test series, z_i the test series no. i to be compared with the reference, z_α the number of reference measurement before the test series, and z_ω the number of reference measurement after the test series.

As a result, the tapping torque efficiency is calculated as

$$TTT_{eff,i}\ [\%] = 100 \times M_{ref,i} \ / \ M_i \ . \tag{5}$$

Considering the equations for the theoretical reference value and the normalized tapping torque efficiency, it is possible to compare the measurement obtained at thread no. 40 with the measurement obtained at thread no. 200. For illustration, measurement values of A-11 are given in Table 5. Tapping torque efficiencies calculated according to Equation 1 (ASTM D5619) significantly vary in comparison to the results obtained by the new Equations 4 and 5. For Lub 3, tapping torque efficiencies range from 110 % to 118 %. These experimental results show that monitoring of the reference value and normalization of the measurements values are required.

In some cases, the comparison of mean torques is expedient, especially when comparing test results of different fluids statistically. For this issue, the introduction of an overall reference value valid for all tools and platforms of the same material combination becomes necessary. To use only normalized and thus comparable data, the equation

$$M_{i,norm} = M_{ref,fix} \times M_i \ / \ M_{ref,i}, \tag{6}$$

for calculation of normalized mean torques $M_{i,norm}$ is proposed, with $M_{ref,fix}$ denoting a fixed and overall reference value valid for the combination of the same tool type, same platform alloy, and same reference fluid. The normalized mean torque $M_{i,norm}$ is similar to the value *average tapping torque corrected* introduced by [4] because of differences between taps of the same type. Adjustment and normalization according to Equations 4, 5, and 6 makes comparisons between test results obtained with different tools and platforms of the same material combination possible. Discarding of taps or platforms becomes redundant.

Table 5: Measured data of A-11 normalized acc. to ASTM and Equation 5

Series *i*	**Fluid**	M_i	$M_{ref,i}$	$TTT_{eff,i}$	TTT_{eff} **acc. to ASTM**
5	Reference	1.673	1.673	100	100
6	Lub 1	1.825	1.825	94	92
7	Lub 2	1.722	1.722	102	97
8	Lub 3	1.523	1.802	118	110
9	Reference	1.845	1.845	100	-

Summarizing the conclusions from Figure 5 and from the derived equations, regular reference measurements are indispensable for comparable tapping torque results and can be used to eliminate the effect of changed tools and platforms by applying the developed equations.

3.3. Carryover effects

Carryover effects due to an impact of the previously used fluid on the tap's surface can cause variability in the first test results with the following fluid. This effect is considered in ASTM D5619 and leads to an elimination of the first two measurement values of the following fluid. Other researchers met the risk of carryover effects by using the reference fluid for one thread before each test run [3].

3.3.1. Effect of the previously used fluid

To investigate carryover effects, tap B-4 was used with three different test fluids in AlMgSi1 (Figure 6a). The abscissa is divided in steps of 16 threads equivalent to the number of holes per series on the test platform. Linear trend lines numerically determined show the slope of tapping torque per series. From thread 1 to 96, a slow falling tendency can be detected for B-4 and reference fluid F2.

Using F12 in the same concentration leads to an increase in tapping torque. The series of F12 itself has a slightly decreasing tendency as well as the following measurement with F11. The measurement with F11 starts at a slightly lower value in comparison to F12. The end reference measurement with F2 starts at a significant higher value than the last measurement of the first reference series. Torque decreases to a similar value as of the first reference measurement. A carryover effect resulting from the fluid change can be detected. The test results are interpreted as follows: Fluid F11 shows a better lubricity than F12. The reference fluid lubricates better than F12.

The carryover effect can also be recognized for tap type C in AlSi7Mg (Figure 6b). In this figure, the gradients of the trend lines are added to examine the carryover effect. From Lub K to Lub P, a decreasing tendency per series of seven threads can be detected (14 holes per column on AlSi7Mg-platform). An increasing tendency is detectable for Lub U. Carryover effects differently influence the following measurement series. Taking the gradient of the trend lines as a feature to evaluate the effect of the previously used fluid, Lub M (lower gradient) is not affected to the same extent by Lub L as Lub L (higher gradient) is affected by Lub K.

Most of the measurement values level off only for the last three or four values (Lub M, O, P, and U). For Lub K and L the values do not level off for the number of measured values. Concluding the experimental results, the carryover effect exceeds the two threads defined in ASTM D5619. Possible reasons for the observed behavior may be the existence of the tribological film built by the previously used fluid or the formation of a characteristic adhered layer belonging to a specific test parameter combination. Ignoring carryover effects leads to less statistical relevant effects and misinterpretations.

3.3.2. Effect of the new methodology on the significance of test results

In the following, results of tapping torque tests (Figure 7a) are statistically analyzed to show the improvement of the new developed methodology by means of an improved statistical significance. The tests were conceived in such a way to be able to compare the results of the standard methodology with the new developed methodology. A reference fluid and the fluids Lub R, S, and T are tested at 10 % concentration in C45E. The fluid Lub T is also tested

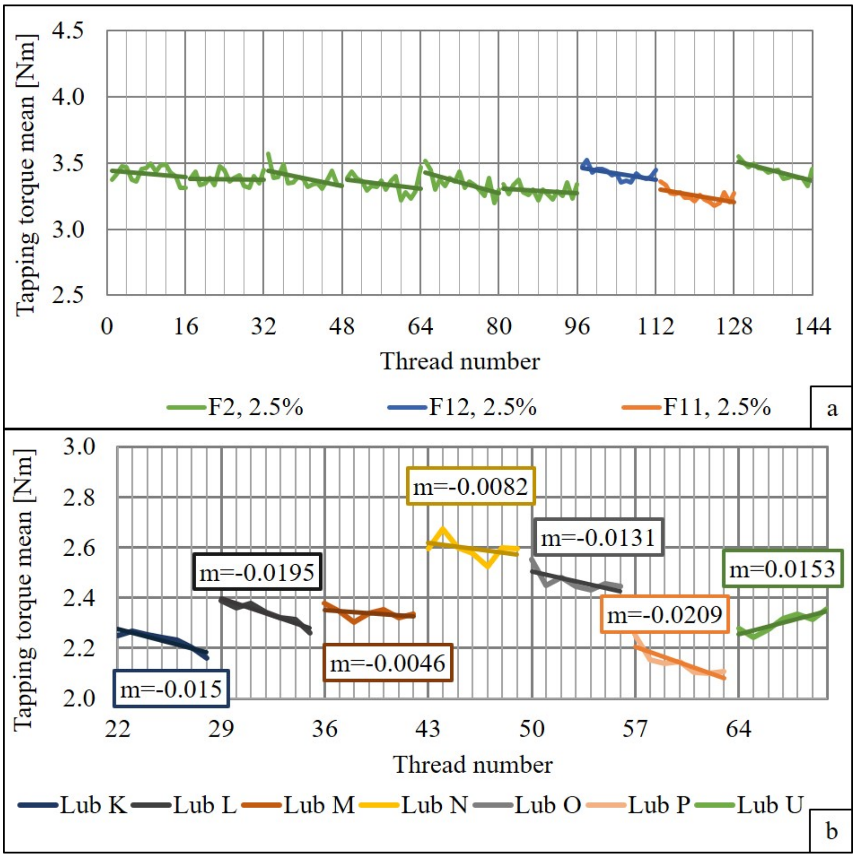

Figure 6: a: Measurements of B-4 in AlMgSi1 to investigate carryover effects from fluid to fluid. A small carryover effect can be detected for the fluids F2, F11, and F12 by the decreasing tendency at the beginning of each measurement with a new fluid. b: Test series and gradients of numerical trend lines for tap C-2 in AlSi7Mg. The gradients vary from fluid to fluid possibly indicating the level of impact.

at 5 % concentration. The fluids significantly vary in lubricating ingredients. Tapping torque tests are performed to show the differences in lubricity for all fluids and for the higher concentration. The reference measurements have similar torque levels and slopes (Ref 1 and Ref 2 in Figure 7a). Significant differences between Ref 1 and Ref 2 are not expected.

Mean torques obtained by ASTM D5619 (approach named *ASTM*) and by two improved approaches are compared to show the necessity of considering a stronger carryover effect and to increase the thread numbers per test run. In the first improved approach *ASTM-16*, 16 threads are performed and the mean is calculated from the last three threads. In the second improved approach *RL-8-8*, 16 threads are performed and the mean is calculated from the last eight threads.

All means are statistically analyzed similar to the analysis in [15]. The torques from the plateau area of the measurement are exemplary checked for normal distribution applying the Kolmogoroff-Smirnov test (Figure 7b). For the significance test, the variances of the means are tested to be equal (F-test). Then, the means are analyzed using a two-sided t-test [26] applying a confidence level of 95 % ($\alpha = 5$ %) and 99 % ($\alpha = 1$ %) to compare these with the

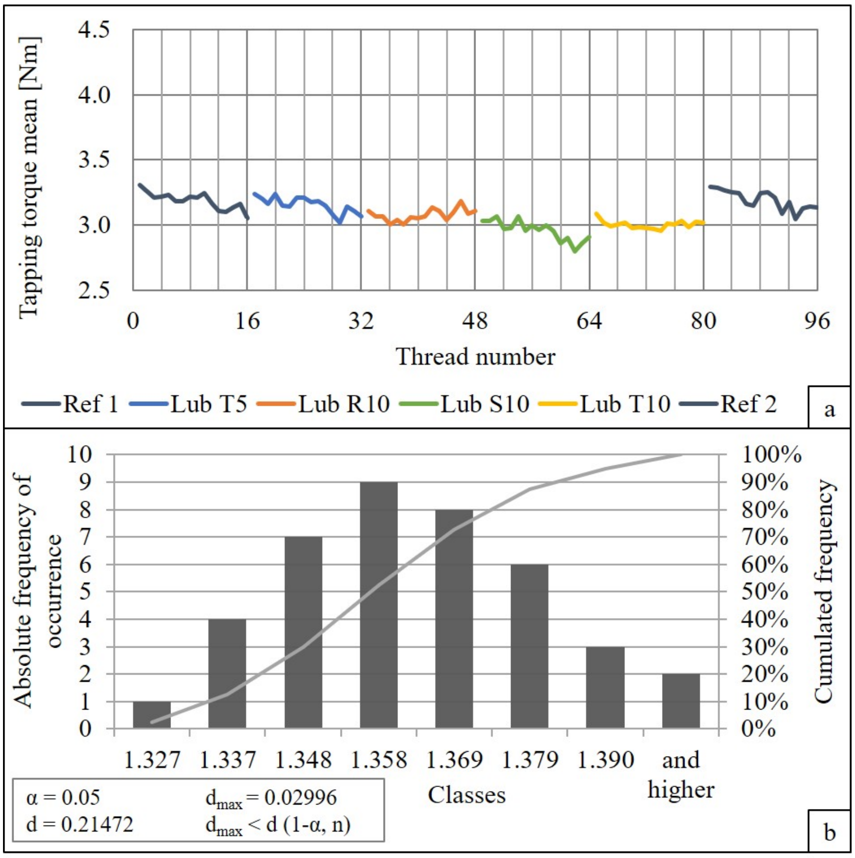

Figure 7: a: Raw data of exemplary measurement series in C45E used for the application of different evaluation approaches and subsequent significance tests. b: Distribution of a single tapping torque measurement in AlMgSi1. Acc. to the Kolmogoroff-Smirnov test, the torque measurement is normally distributed. The two-sided t-test can be applied for significance tests. A normal distribution is also assumed for other workpiece materials.

resulting p-values.

Results obtained by ASTM D5619 and by the improved approach are given in Table 6. In both approaches, the number of contributing values is held constant to investigate only carryover effects. Applying *ASTM*, a significant difference between Ref 1 and Ref 2 and between Lub T5 and Lub T10 can be detected. Differences between Lub S10 and T10 or Lub S10 and R10 are not obtained. In one of four cases, approach *ASTM* provides sufficient test results. In comparison, approach *ASTM-16* gives sufficient results in all cases. Assuming a carryover effect for 15 threads instead of two threads leads to a better differentiability of test fluids in the shown example.

Results from Table 6 are based on a 95 % confidence level. To increase the reliability of tapping torque test results, the confidence level can be increased. A confidence level of 99 % makes a differentiability more difficult so that approach *RL-8-8* is applied to obtain distinguishable test results further. New results obtained by approach *ASTM-16* and by approach *RL-8-8* at a 99 % confidence level are given in Table 7.

As a result of higher confidence level, the effectivity of approach *ASTM-16* decreases from four to two cases: A

Table 6: Results of significance test with $\alpha = 0.05$. Approach *ASTM-16* achieves better results than *ASTM*.

Compared fluids	**Difference expected?**	**Result acc. to *ASTM***	**Result acc. to *ASTM-16***
Ref 1 vs. Ref 2	no	yes p=0.0012	no p=0.3064
Lub T5 vs. T10	yes	yes p=0.0036	yes p=0.0172
Lub S10 vs. T10	yes	no p=1.0000	yes p=0.0119
Lub S10 vs. R10	yes	no p=0.4535	yes p=0.0034

Table 7: Results of significance test with $\alpha = 0.01$. Approach *RL-8-8* achieves better results than *ASTM-16*.

Compared fluids	**Difference expected?**	**Result acc. to *ASTM-16***	**Result acc. to *RL-8-8***
Ref 1 vs. Ref 2	no	no p=0.4070	no p=0.9664
Lub T5 vs. T10	yes	no p=0.0172	yes p=9.7E-5
Lub S10 vs. T10	yes	no p=0.0118	yes p=0.0047
Lub S10 vs. R10	yes	yes p=5.1E-6	yes p=0.0034

difference between Lub S10 and R10 can not be obtained anymore but a difference between the reference measurements Ref 1 and 2. The improved approach *RL-8-8* is successful in all four cases: Significant differences can be detected between the two different concentrations of Lub T and between the fluids Lub S10 and T10 or R10. The reference measurements are evaluated to be statistically equal. Concluding, increasing the number of torque values contributing to the mean leads to a better differentiability of test fluids especially for higher confidence levels.

4. Summary and conclusions

Tapping torque tests are used to evaluate the performance of metalworking fluids. The existing standard ASTM D5619 of 2011 has been withdrawn 2016 with no replacement. Independent from the withdrawal, metalworking fluids have to be evaluated with a laboratory test transferable into practice and flexible enough to reflect the numerous possibilities of tool material and workpiece material combinations. In this article, problems with the last active version of this standard are discussed and improvements are proposed to increase comparability and significance of test results for a new version. This contribution does not deal with the finding of the best suitable fluid for a specific application. Here, test procedures and evaluation methods are focused. It is found out that the previously fixed definitions lead to high experimental cost, no comparability between taps or workpieces, and less significance of test results. In the review section, tapping processes used to evaluate the performance of metalworking fluids and especially the used test procedures and evaluation methods are reviewed.

The aim of the present investigations is to overcome the disadvantages discussed and therefore to increase significance and comparability of tapping torque test results obtained with coated forming taps. To illustrate the real problems, as example three different workpiece materials (AlMgSi1, C45E, and AlSi7Mg) are used to evaluate the effect of tool, platform, or fluid changes on the test results. The running-in behavior of two different forming taps is investigated. Strongly varying results are obtained for the same tool-fluid-workpiece combination. A criterion to determine the end of a tap's running-in phase is proposed and exemplary applied for the tap qualification defined in ASTM D5619. From the experimental results, it can be clearly concluded that the qualification criterion defined in ASTM D5619 is too strict and leads to an high amount of disqualified taps.

The need for regular reference measurements is shown by appropriate tests over a higher amount of threads. New definitions (equations) are introduced to normalize the measurement values by the changed reference value. Concurrently, these new equations meet the requirements to integrate disqualified taps into the test evaluation. Applying the suggested definitions, the comparability of test results between taps and platforms of the same material pair combination can be clearly enhanced.

In this contribution, the phenomenon of carryover effects when changing test fluids during a tapping torque test is investigated by applying statistical significance tests. For the chosen fluid sequence, the carryover effect exceeds the two threads defined in ASTM D5619. The analysis of different examination approaches shows that considering a stronger carryover effect and increasing the number of threads per test series enhances the differentiability between test fluids even by applying a higher confidence level. The results can be summarized as follows:

1. The running-in phase has to be checked for each tap: Even taps of the same material and type can have different running-in phases. The workpiece material can also affect the running-in behavior. A criterion based on the measure *torque mean* is introduced to identify the end of running-in. The optical examination of built-up edges or adhered layers becomes redundant and saves time for test conduction. The starting condition for tapping torque tests is clearly defined.
2. Regular reference measurements are indispensable for comparable tapping torque tests: The tap continuously wears off and the reference value changes over the increasing number of tapping torque tests. Test results are significantly affected and may lead to misinterpretations. Regular reference measurements lead to more reliable data and comparable test results over the whole life time of the tool. The authors propose repetitive reference series after every sixth test series.
3. New calculation methods normalizing the measurement values by the theoretical recent reference value are introduced. These equations make comparisons between disqualified taps and workpieces of the same material possible although such comparisons were not intended in ASTM D5619. Then, taps being disqualified according to the allowed 2 % range can be used for tapping torque tests. Comparability is improved and costs for experiments are saved.
4. More threads have to be discarded because of carryover effects. The effect of the previously used fluid on the following measurement result is stronger than the two threads defined in ASTM D5619. Eight threads are evaluated to be sufficient and reliable. Test fluids are easier to distinguish because of smaller deviations of the

contributing values. The usefulness of tapping torque tests is significantly improved.

5. The thread number per test fluid has to be increased. The test procedure according to ASTM D5619 leads to worse distinguishability between test fluids because the mean calculation is only based on three single values. Increasing the number of contributing values to eight leads to differentiability even at higher confidence levels. Reliability and significance of tapping torque test results are increased.
6. Using the proposed test procedure and evaluation approach, coated tools can be used for tapping torque tests. Coated tools are used in field applications because of better performance and longer tool life. The proposed changes lead to results with smaller deviations and clearer differentiation options. As a result of the improvements, it is possible to reflect field conditions more accurately.

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