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PAPER

CRIMINALISTICS

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Angular Determination of Toolmarks Using a Computer-Generated Virtual Tool*

ABSTRACT: A blind study to determine whether virtual toolmarks created using a computer could be used to identify and characterize angle of incidence of physical toolmarks was conducted. Six sequentially manufactured screwdriver tips and one random screwdriver were used to create toolmarks at various angles. An apparatus controlled tool angle. Resultant toolmarks were randomly coded and sent to the researchers, who scanned both tips and toolmarks using an optical profilometer to obtain 3D topography data. Developed software was used to create virtual marks based on the tool topography data. Virtual marks generated at angles from 30 to 85° (5° increments) were compared to physical toolmarks using a statistical algorithm. Twenty of twenty toolmarks were correctly identified by the algorithm. On average, the algorithm misidentified the correct angle of incidence by −6.12°. This study presents the results, their significance, and offers reasons for the average angular misidentification.

KEYWORDS: forensic science, statistical comparison, computer simulation, algorithm, toolmark, virtual toolmark

Recent history has seen scientific testimony challenged in numerous court cases since the *Daubert v. Merrell Dow Pharmaceuticals, Inc.,* ruling. In particular, comparative forensic examinations such as firearms and toolmark examination have been increasingly challenged by attorneys due to the perceived subjective nature of the examination and the mistaken impression that there is a lack of scientific studies aimed at addressing its primary assumption, namely, that all tools produce a unique toolmark. Scores of studies have been conducted and published in the Association of Firearm and Tool Mark Examiners (AFTE) Journal to validate comparative forensic examination (1,2), and give credence to the assumption that every tool contains a unique surface topography capable of creating a unique mark if used against another surface. A number of more recent studies using objective computer-based algorithms have shown toolmarks created by the same tool will statistically be more similar than toolmarks created by similar tools, even when the tools are manufactured sequentially (3–5). Nichols (1) has written a thorough literature review that responds to many criticisms of forensic examination.

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The large body of work that currently exists has not stopped judicial challenges, however, since in many instances, published studies still rely on what is considered a subjective assessment. Even though current methods have been shown to produce false identification rates of *c.* 1% (1), ideally what is desired is an entirely objective analysis that can provide known error rates that are similarly low.

Current research has focused on the use of computers and algorithms to increase the robustness of tool–toolmark identifications. Several different approaches have been made. Chumbley has used a nonparametric Mann–Whitney *U*-statistic (referred to as T1) to compare three-dimensional topography data obtained using an optical profilometer (4). Toolmarks made using screwdriver tips at various angles were compared. Results from this study were in agreement with experiential evidence from forensic examiners. T1 values were largest (e.g., increased probability of a matching pair) when toolmarks created by the same screwdriver tip edge and angle were compared. An angular dependence for screwdriver toolmarks was also found by Bachrach et al. (6). It was concluded from this study that screwdriver toolmarks created at different angles can appear to be completely different toolmarks. Specifically, results from this study showed comparisons of screwdriver marks at 15° and 45° angles made on the same medium had an error rate of *c.* 50% (6).

Wei et al. (7) has proposed the use of correlation cells for rapid ballistic identifications. Correlation cells, select regions on a surface, can incorporate three-dimensional topography data for quick matching between marks. An initial test utilized cartridge cases fired from ten sequentially manufactured pistol slides. Three-dimensional topography data were obtained using a confocal microscope and analyzed under the constraints that three of three correlation cells must show positive or negative correlation for known and unknown matches, respectively, to be declared. Initials results of this methodology yielded no false-positive or false-negative identifications (7).

Petraco et al. (5) has applied machine learning to analyze striation patterns on cartridge cases fired from 9 mm Glock pistols and screwdriver marks made in lead. A confocal microscope was used to measure three-dimensional topography data from each toolmark. There were 162 profiles measured from 24 Glocks and 290 profiles measured from 58 screwdriver edges (29 screwdrivers). Simulated mean profiles based on the real data resulted in 720 total profiles from the Glocks and 1740 total profiles from the screwdrivers available for analysis. Initial algorithmic identifications on subsets of the total collected data found an error rate of 2.5% for the Glock toolmarks with a 95% confidence interval of 1.3–3.2% and an error rate of 6.5% for the screwdriver marks with a 95% confidence interval of 3.5–10%. Further refinement of the pattern recognition process through increasing the analyzed data sets reduced error rates to 0.03% and 0.01%, respectively (5). The results were good and demonstrated the capability of pattern recognition in toolmark analysis.

The aforementioned studies, and the study to be presented, show that computer-based systems can be valuable aids in forensic examinations. In this study, the ability to specifically characterize a tool surface and relate that surface to the mark that tool could be expected to generate under any given set of conditions is demonstrated. The analysis involves a completely objective assessment of the tool surface which is then used to create a computer-generated "virtual tool" that can be manipulated at will by the forensic examiner to create any number of "virtual toolmarks". When combined with a statistical algorithm for making comparisons, it then becomes possible not only to directly relate a tool to a toolmark but also to predict with a high degree of accuracy the conditions that existed (specifically, angle of attack) when the toolmark was made.

Experimental Methodology

Sample Generation

A blind study was devised where six sequentially manufactured screwdriver tips and one randomly selected screwdriver from another manufacturer (treated as an unknown) were used by a forensic examiner to create a series of 20 toolmarks. Researchers were kept ignorant of the correct tool–toolmark combinations throughout the experiment. Toolmarks were created on *c.* 1.5 by 1.5 inch lead plates using the jig shown in Fig. 1. Different fixtures allow toolmarks to be made at angles ranging from 30 to 85° in 5° increments. For this study, the examiner was instructed to use any angle they wished as well as either side of the screwdriver. This allowed 168 possible combinations of tool and angle used to create marks when both sides of the screwdriver are considered.

Ultimately, 20 toolmarks were made. Toolmarks were labeled with randomly generated three digit ID tags and sent to the research group. An answer key containing the correct combinations of tool–toolmarks was kept in a sealed envelope until the research group presented their identifications.

Surface Characterization

After receiving the tools and toolmarks, the surface topography was obtained from the six screwdriver tips and the created toolmarks using an optical profilometer (Alicona InfiniteFocusSL, Raaba/Graz, Austria.). This equipment employs focus variation to scan and obtain accurate three-dimensional topography data. Focus variation works through a precisely controlled *z*-axis that is able to bring varying portions of the surface into focus. When an object is in focus, the object sharpness (function of light returned to sensor) is at a maximum. The sharpest data for each pixel are then used to construct the three-dimensional topography (8). An *c.* 2×7 mm^2 area of topography data were obtained from each toolmark. The most completely toolmarked areas of the substrate were selected for analysis. An example of one lead plate with a labeled toolmark showing the area scanned is shown in Fig. 2.

Each side of the screwdriver tips was scanned at a 45° angle relative to the vertical axis of the infinite focus microscope objective. An apparatus was used to hold the screwdriver tips at precisely the same angle for each scan. Figure 3 shows an example of the portable scanning equipment and the apparatus holding a screwdriver tip.

Each data set (from both toolmark and screwdriver tip) had a horizontal pixel resolution of 3.914 μm and vertical resolution of 1.007 μm. Scans were completed at a 10× magnification. Approximately 5 min were needed to obtain data from each sample.

Noise Reduction

Any method of automated data collection will contain noise due to random variables. In using an optical system, noise (e.g., artifacts such as small spikes or holes) can be generated by imperfections that greatly alter the normal scattering of light collected from the surface that is used for generating an image. To fix this issue and to eliminate unneeded data, a cleaning procedure is required.

Before an automated statistical algorithm can be used, the operator must ensure that the data to be compared only contain information relevant to the comparison. For example, Fig. 4 shows the complete scan obtained from a toolmarked surface.

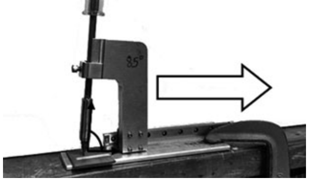

FIG. 1—*Photograph of jig used to create toolmarks. The 85° angle holder is in use and the direction of the manually applied force is indicated.*

FIG. 2—*Example toolmark used in the study.*

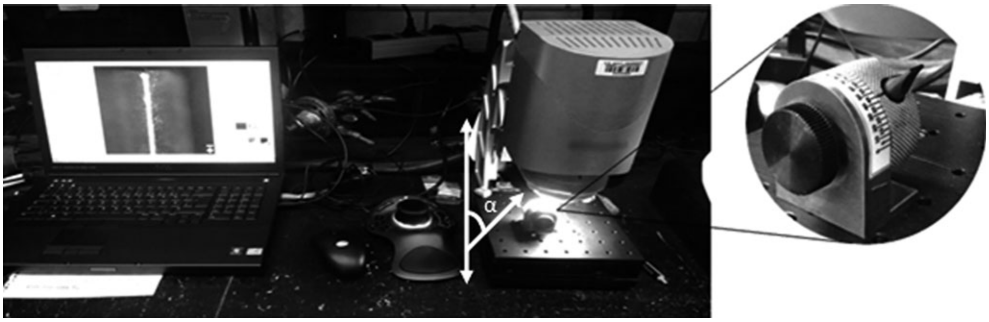

FIG. 3—*Scanning equipment and apparatus for holding screwdriver tip (45° angle defined).*

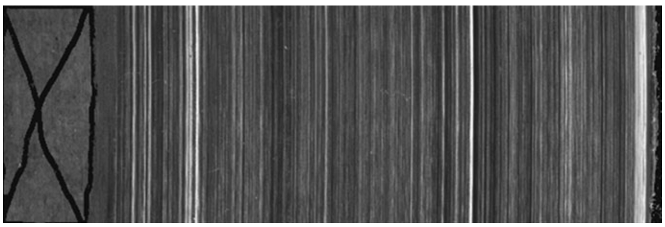

FIG. 4—*Toolmark 556 (dimensions* c. *7 × 2 mm) during masking process.*

As the goal is to compare the toolmark, not the unmarked surface of the lead plate on which the mark is made, extraneous data at the edges of the scan must be removed. Software named Mask Editor was developed to allow manual cleaning of each data set. A "painting" tool allows the user to manually paint over (mask) areas of unneeded data without altering the data itself; painted regions are simply ignored in further analysis. The software is programmed to find the largest contiguous unmasked region, so the masking process is not tedious.

After masking, spike artifacts on the screwdriver tips are dealt with through the use of a seventh-order polynomial that was applied to each row and column within a data set. Any data points with a depth 100 μm greater or less than the predicted value were removed. This threshold was determined through experimentation. Any small holes (20 pixels or less in diameter) in the data were then filled using linear interpolation. Toolmarks were detrended to remove small angular differences (relative to the *z*-axis of the optical profilometer) that occur when scanning multiple samples (9).

Data Comparison

Once cleaned, the data sets were suitable for comparisons using a developed software suite and the previously developed algorithm (4). Termed the Mark ANd Tool Inspection Suite (MANTIS) this software was developed to allow comparisons of toolmarks with actual marks or virtual marks generated from three-dimensional tool topography. A full overview of the virtual mark generation procedure is given in (10), and the reader is directed there for complete technical details. Briefly, the software uses the tool data set that was scanned and cleaned at a known angle to generate a virtual surface that can be rotated to any angle one wishes to investigate. The edge of the screwdriver may be thought of as being analogous to a mountain ridge. If one were to superimpose a coordinate system, *X* would be the direction perpendicular to the ridge, *Y* the direction along the ridge, and *Z* the height above sea level. As one hikes along the ridge, you are always at the highest point on the ridgeline (in an *XZ* plane), even though you encounter small peaks and valleys on your walk. So it is with the toolmark. Figure 5*a* shows a reconstructed virtual image of the screwdriver edge, and it is clear that as you move along the "ridge" in the *Y* direction, 2D cross sections (*XZ* planes in the shown coordinate axis) taken at any point will produce a profile similar to that shown below the virtual image. By finding the highest topographical point in all possible 2D cross sections moving along the *Y* direction, a virtual "effective" topography profile (*YZ* data) is constructed of the ridgeline, which captures all the peaks and valleys encountered as you proceed along the crest.

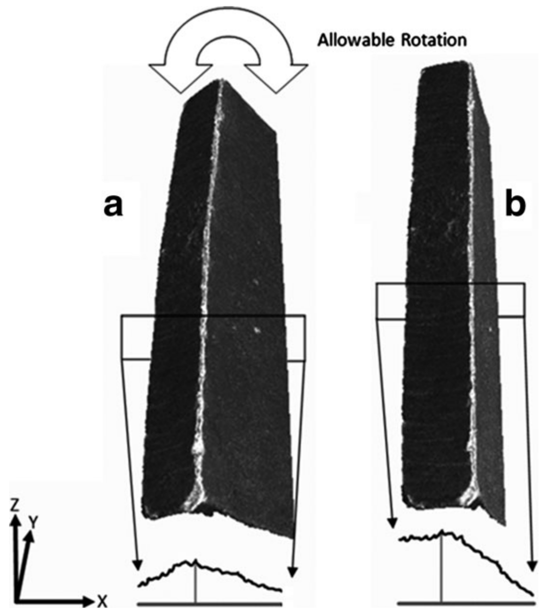

FIG. 5—*Generic screwdriver tip with highest topographical point found for one cross section at two different angles (a, b).*

Suppose one now tilts the screwdriver. While peaks and valleys still exist in the *Y* direction, the surface topography that results due to the tilt means that the location of the crest may change. It is possible that for any specific *XZ* plane what was once a low point below the crest now becomes the highest point of the ridge, as shown in Fig. 5*b*. In other words, the *YZ* data generated at the first angle are altered when tilting to the second angle. In creating a virtual mark, the highest points at any angle (i.e., the crest of the ridge containing both peaks and valleys) are assumed to be the first points to contact another surface and therefore are the primary cause of the striae observed in a

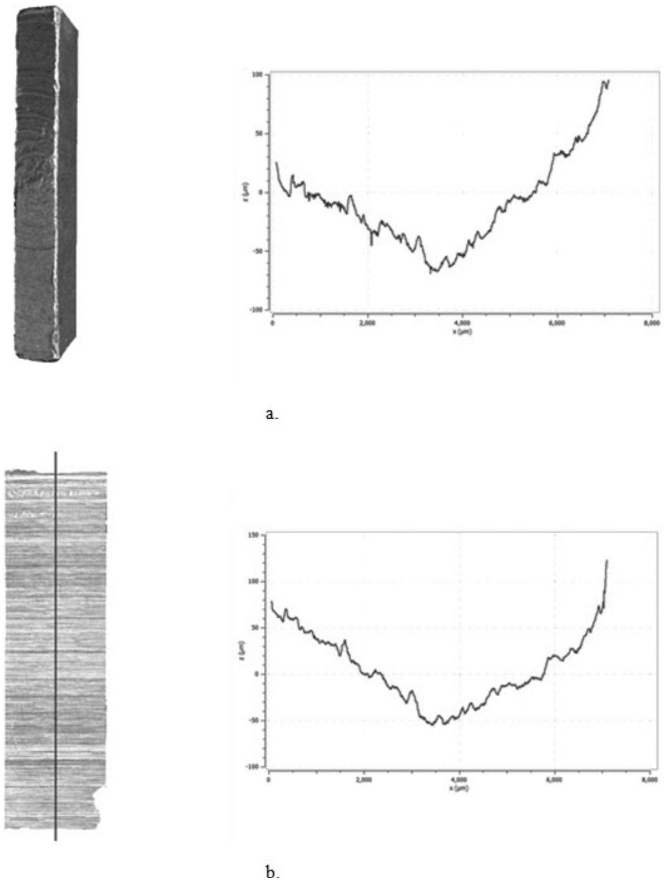

FIG. 6—*(a) Virtual mark generated at 75°. (b) Corresponding physical toolmark created at 75°.*

toolmark. By taking the effective virtual tool topography at the crest of the ridge at any angle and virtually "dragging" it against a virtual substrate (i.e., expanding the *YZ* data in the "*X*" direction), a virtual toolmark is generated and it is this topography that is compared to the physical toolmark. The process virtually mimics the actions performed by a forensics examiner—using a test mark created by marking a substrate with a suspect tool to compare to an evidence mark. This first-level approximation does not account for material properties, applied force, or the other two rotation axes; it was assumed the effective topography was fully transferred and the virtual mark resulting from this process is "basically" the inverted effective tool topography. The complexity of the virtual marking process will allow for higher level approximations in the future where the sliding action of the virtual tool against the virtual substrate has a large impact on the results.

Figure 6 shows an example of a virtual toolmark created by characterizing the tooltip as compared to data obtained from the corresponding physical toolmark. The solid line crossing the physical toolmark represents the path trace that produced the profile data shown.

The MANTIS software was used to generate virtual toolmarks at angles from 30 to 85° at 5° increments for each screwdriver tip and perform comparisons with physical toolmarks using the statistical algorithm discussed in Ref. (4). For this study, three combinations of user-determined parameters were used. Multiple parameter sets were used to see whether the results varied due to

TABLE 1—*Algorithm input parameters.*

Parameter Set	Search Window	Validation Window
1	500	200
2	500	500
3	800	800

different user-input. Parameters that were varied include the pixel widths of search and validation windows as shown in Table 1.

The algorithm outputs a single T1 statistic for each comparison. Three parameter combinations, twelve angles, twelve effective screwdriver tip edges (N.B. the unknown screwdriver was not examined), and 20 toolmarks led to 8640 T1 values. Based on observations in (10, 3, and 4), a maximum T1 value is expected to occur when there is a statistical likelihood of a match. This will only occur if the correct combination of virtual mark, angle, and toolmark is compared. The T1 value is also expected to decrease as comparisons are made of similar marks made at angles varying by >10° (4,11).

A heuristic critical value was used to determine whether the T1 output corresponded to a matching tool–toolmark combination. It is known that for matching pairs, the statistical distribution of T1 depends on many factors and cannot be derived analytically based on what is currently known. For nonmatching pairs, observations show that the distribution of T1 is closer to that suggested by simple theory (approximately normal with zero mean and unit variance), but cases have occurred where this does not agree with experimental data. Hence, for this study, a value was heuristically chosen. A T1 value >6 was heuristically treated as the critical identification criteria—if the standard asymptotic distribution theory held, this would correspond to incorrectly identifying a nonmatching pair as matching with an extremely low probability. The toolmark and creation angle were identified as matching by the maximum T1 value above the critical value.

Results

Figure 7 shows the identification process graphically using both matching and nonmatching tool–toolmark combinations from the results of this study. For reference, screwdriver tips are named using a simplified scheme (e.g., T20A where the number can range from 20 to 25 for the six different tips and either an A or B is present to differentiate between the two tool edges) and toolmarks were named using randomized three digit ID codes. T1 values from this example show the nonmatching pair fluctuated between *c.* −4 and 3, but never above the critical value of 6—consistent with a nonmatching comparison. The shown matching pair T1 values were above the critical value from 30 to 45° with the maximum value occurring at 35°. These results would indicate that the algorithm had identified toolmark 408 as being created by screwdriver tip T20A at 35°. The algorithm was able to identify the correct tool–toolmark combination over an angular range of −5 to +10° (30–45°). This methodology was repeated for each parameter set over all possible combinations to determine the matching pairs.

Results from the identifications are shown in Table 2. Utilizing only the algorithm and virtual marking, every toolmark (20/20) was correctly paired with the screwdriver tip edge that created it, with toolmarks from the additional unknown screw-

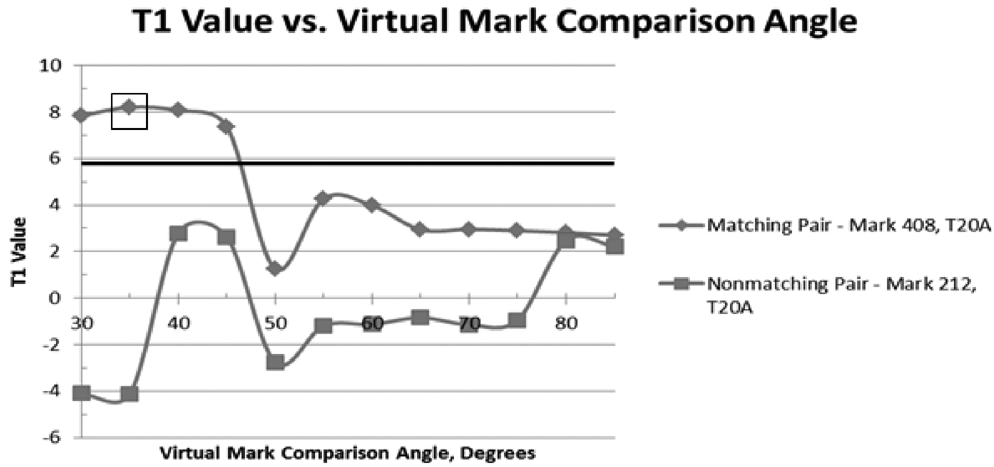

FIG. 7—*Statistical output using parameter set 2 as a function of angle.*

TABLE 2—*Tabulated results from the study.*

Toolmark	Answer Key	Parameter 1	Parameter 2	Parameter 3	Avg. Angle Mismatch (°)
Screwdriver Identification					
420	T23B at 75°	T23B at 70°	T23B at 70°	T23B at 70°	−5.0
408	T20A at 40°	T20A at 35°	T20A at 35°	T20A at 35°	−5.0
787	T24A at 55°	T24A at 45°	T24A at 45°	T24A at 45°	−10.0
556	T22B at 65°	T22B at 55°	T22B at 60°	T22B at 60°	−6.7
621	T21A at 45°	T21A at 35°	T21A at 35°	T21A at 35°	−10.0
983	T25A at 45°	T25A at 35°	T25A at 35°	T25A at 35°	−10.0
872	T20B at 60°	T20B at 55°	T20B at 55°	T20B at 55°	−5.0
648	T25A at 60°	T25A at 55°	T25A at 50°	T25A at 55°	−6.7
552	Unknown at 30°	No match	No match	No match	–
514	T22A at 30°	No match	No match	T22A at 30°	0.0
416	T23A at 70°	T23A at 60°	T23A at 65°	T23A at 65°	−6.7
916	T21A at 70°	T21A at 60°	T21A at 60°	T21A at 60°	−10.0
409	Unknown at 70°	No match	No match	No match	–
423	T24B at 80°	T24B at 70°	T24B at 70°	T24B at 70°	−10.0
212	T20B at 80°	T20B at 75°	T20B at 75°	T20B at 75°	−5.0
394	T25B at 40°	T25B at 35°	T25B at 35°	T25B at 35°	−5.0
674	T21B at 40°	T21B at 35°	T21B at 30°	T21B at 30°	−8.3
448	T24B at 40°	T24B at 40°	T24B at 40°	T24B at 35°	−1.7
286	T23B at 40°	T23B at 35°	T23B at 40°	T23B at 35°	−3.3
616	T22A at 75°	T22A at 75°	T22A at 75°	T22A at 70°	−1.7
Avg. Range		−7.6°, +9.4°	−11.8°, +12.4°	−11.7°, +13.6°	Avg. Mismatch −6.12°

driver being identified through exclusion. No false positives occurred during identifications. On average, the maximum T1 value occurred at an angle 6.12 degrees less than the answer key creation angle. The average range in Table 2 refers to the average angular range that the algorithm was able to identify matching tool–toolmark combinations—for parameter set 3, the algorithm identified matching tool–toolmark combinations on average from 11.7° less than the maximum T1 value to 13.6° greater than the maximum T1 value. This means the algorithm calculated a T1 value greater than the critical value over a total range of 25.3 degrees.

Discussion

Correctly identifying every toolmark provided validation of both the comparison algorithm used and the ability to create a virtual toolmark that accurately reflects what can be expected in real life. These results open up a number of possibilities for the future use of virtual markings, both in the area of basic science and applied research.

Although initial results are promising, deficiencies were observed in the results. The first deficiency is the clear bias of the maximum T1 value occurring at lower angles than the creation angle. Deflection of the jig was investigated as the potential cause as the direction of deflection would naturally lower the true creation angle. Figures 8–10 show photographs captured from slow motion video recorded while creating additional toolmarks. The deflection was measured using photo imaging software on the photographs for toolmarks created at 30, 55, and 85°. Measurements revealed a deflection of *c.* 2–4° can occur during toolmark creation caused by movement of the screwdriver tip in the holder and not deflection of the screwdriver tip holder. However, a 2–3° deflection during toolmark creation explains much of the apparent angular bias in the results. As virtual marks were compared to toolmarks in 5° increments, and a 3° deflection occurring during toolmark creation was possible, it is

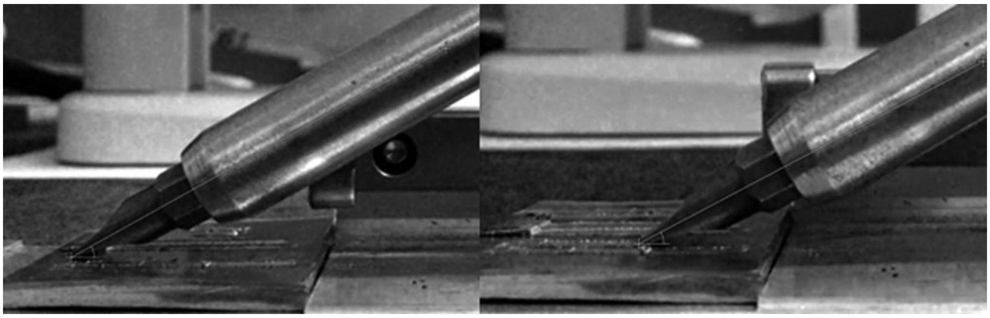

FIG. 8—*Before and during toolmark creation, measured angles of 29.5° and 27.8°, respectively.*

FIG. 9—*Before and during toolmark creation, measured angles of 54.6° and 52.8°, respectively.*

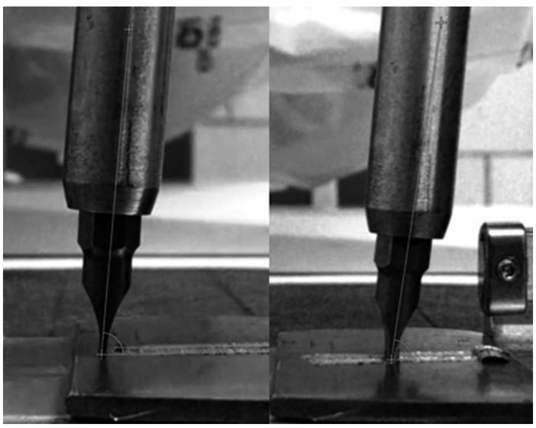

FIG. 10—*Before and during toolmark creation, measured angles of 85.1° and 81.6°, respectively.*

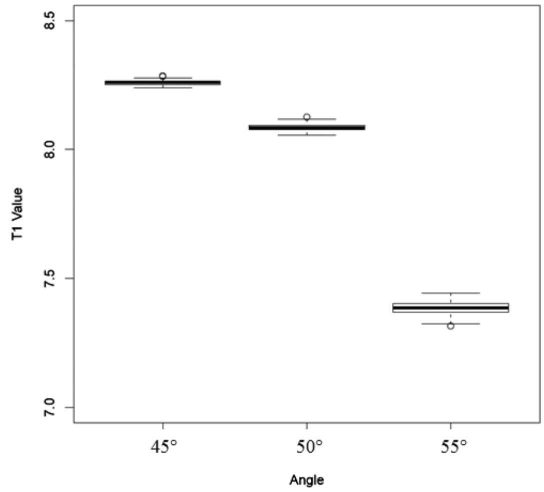

FIG. 11—*Output variation of repeated comparisons.*

not surprising that the virtual mark 5° less than the nominal creation angle would have higher correlation with the toolmark.

The second deficiency was observed with Toolmark 514. Two parameter settings failed to identify Toolmark 514 (two false negatives). As this toolmark was nominally created at 30°, and compared to a 30° virtual mark, it was thought that deflection may have played a role in this lack of identification. Toolmark 514 was compared to a 25° virtual mark; however, T1 values were still well below the critical value for the two parameter settings. Inspection of the data revealed that for parameter settings 1 and 2, the regions of highest correlation were found between two prominent topography features that were not actually related. The larger sized parameter setting 3 was large enough to distinguish between the prominent topography features—resulting in the correct identification of the tool–toolmark combination. In other words, careful examination of the data is necessary when conflicting results are obtained for different parameter settings to ensure that the computer is truly conducting a valid comparison.

The final deficiency investigated was instances where the maximum T1 value occurred when the angle was 10° lower than the creation angle, as occurred for toolmarks 787, 621, 916, 983, and 423. Algorithm output variation was investigated as a possible cause of this deficiency in the results. The comparison algorithm utilizes random number generation during analysis to select toolmark profile regions for correlation computation (4). Due to the use of random numbers, the same T1 value is not computed for repeated comparisons—there is a small amount of output variation.

To test this, Toolmark 787 and its corresponding screwdriver tip T24A were used for repeated comparisons. Toolmark 787 was created using a 55° holder. However, the maximal T1 value was computed at 45°. To determine whether output variation was the potential cause of an additional 5° of error after error due to deflection, 50 comparisons were performed using parameter set 2 at 45, 50, and 55°. The results are presented in Fig. 11 using box plots. The box plots are composed of a solid black line representing the median value, boxes representing the 1st and 3rd quartiles (bottom and top of the box, respectively), whiskers representing a maximum of 1.5 times the interquartile range, and circles to represent outlier data points. The box plots show complete separation of each measurement, indicating output variation is not a likely cause of this deficiency.

While every attempt is made to control the creation of the toolmarks, there are inherent fluctuations in the applied force during toolmark creation. Fluctuations in applied downward force are caused by the relative alignment of the jig to the lead plate. The screwdriver will not be aligned perfectly within the jig before each use, and the lead plate thickness varies between samples (lead plates were purchased at the same nominal thickness). These factors result in fluctuations of the applied force and ultimately the topography of the created mark. This inherent variation may be the cause of some of the observed error.

Summary and Conclusions

Twenty of twenty tool–toolmark combinations were correctly identified, and the marking angle reasonably estimated, in a blind study comparing virtual toolmarks created by analyzing a tooltip to actual toolmarks by means of an objective statistical algorithm. On average, virtual marking estimated the angle of creation within *c.* 5° of the true angle of creation. The results from this study indicate that toolmarks are most identifiable using the employed algorithm when made within *c.* 10° of each other.

Deficiencies in the results were addressed. The heuristically chosen critical T1 value, while useful, is not entirely defensible due to the dependence of the matching pair T1 statistical distribution on input parameters. It was also found that 2–3° of deflection occurs during toolmark creation. The deflection was the root cause of some of the estimated angular inaccuracy. If 3° of deflection occurred during toolmark creation, it is expected that the virtual mark 5° lower than the nominal creation angle would have higher correlation with the toolmark. In instances where the maximal T1 value occurred at an angle 10° off of the nominal creation angle, it was found that inherent variation of the calculated T1 values was not a factor. It is likely that 5 of the 10° is due to deflection while the remaining 5° of angular mismatch was possibly due to inherent variation of the applied force during toolmark creation.

This first-level study provided validation for the concept of creating "virtual toolmarks" as an aid in the identification process by directly relating a tool to a mark and in allowing determination of certain parameters related to the marking. Evidence that a fixed angular range exists over which toolmark identifications can occur was found—in agreement with prior studies that indicate an identification angular range exists (12). Virtual marking could ultimately serve as a useful tool to aid forensic examiners in more accurately estimating toolmark angles, speeding analysis, as a training tool, and in obtaining basic information concerning perception of what does or does not constitute a match. Finally, this study provided further validation of the primary assumption of comparative forensic examination, namely, that even sequentially manufactured tools contain identifiably unique topographies.

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