2D and 3D Topography Comparisons of Toolmarks Produced from Consecutively Manufactured Chisels and Punches

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ABSTRACT

A 2009 report by the National Academies [1] recommended strengthening the scientific basis of procedures and criteria employed by the forensic science specialty of toolmark identification. The current method of comparison and determination of identity is conducted by a trained examiner using a comparison microscope. However, the ultimate conclusion of the comparison is subjective in nature and is affected by the examiner's skill and experience. This study seeks to evaluate whether a mathematically objective metric, the maximum value of the normalized Cross Correlation Function (CCF_{MAX}), can be employed to identify the tool that generated a striated or impressed toolmark from a pool of consecutively manufactured tools. The metric will be applied to the measured surface topography of toolmarks generated under laboratory conditions on a near pristine surface. A device was designed for the controlled generation of toolmarks. Two types of representative tools were selected: chisels for making striated toolmarks and drift punches for making impressed toolmarks. For striated toolmarks, a 2D stylus instrument was used to capture the toolmark topography. Impressed toolmark topographies were captured using a 3D disc scanning confocal microscope. The comparisons were blind, with fully automated data analysis and identification. Based on the CCF_{MAX} metric and a statistical analysis of the known match and known non-match scores, all the unknown toolmarks were correctly identified to the tool that created them. This study provides additional objective scientific support for the validity of toolmark identifications.

Introduction

Toolmarks are permanent changes in the topography of a surface created by forced contact with a harder surface (the tool). Common tools used at crime scenes are: hammers, crow bars, wire cutters, chisels, screwdrivers, and punches. The forensic science specialty of "firearm identification" is a subset of "toolmark identification." A trained examiner may render an opinion as to whether a specific tool generated questioned toolmarks based on the observed level of agreement between the pattern of the questioned toolmarks and the pattern of the toolmarks generated by the tool in a laboratory setting. The examiner assesses the significance of the agreement on the basis of training and experience with the level of agreement found between toolmarks known to be made by different tools in contrast to the level of agreement between toolmarks known to be made by the same tool. Toolmarks are generally classified as either striated or impressed. Striated toolmarks are created when the tool is moved across a surface, resulting in a surface topography that has the appearance of parallel lines, called striae. Impressed toolmarks are created when a tool impacts or presses against another surface, resulting in a surface topography that mimics a negative copy of the tool surface topography. For there to be a potential for toolmark identification, the tool working surface must have individuality and produce reproducible toolmarks for comparisons [2]. In general, toolmarks have class characteristics that are common to a certain tool brand and model, sub-class characteristics common to a certain batch of manufactured tools, and individual characteristics arising from random variations in tool manufacturing, use, and wear. The latter type of characteristics, usually microscopic in nature, forms the basis for toolmark identification.

Currently, optical comparison microscopes are used to assist examiners in identifying toolmarks to potential tool sources. Through their many years of training and experience, examiners are able to judge whether or not toolmarks came from the same tool. This current practice of optical reflectance microscopy produces images representing optical contrast variations that provide, through slope variations and shadowing, only an indirect measure of surface topography. The images obtained are affected by lighting conditions, multiple reflections, exposure settings, and variations in surface reflectivity (including color) [3].

In 2009, the National Academies published the report "Strengthening Forensic Science in the United States: A Path Forward [1]." This report called into question, amongst other issues, the objectivity of conclusions based on visual toolmark identification by examiners. A major concern is the lack of precisely defined, and scientifically justified, protocols that yield objective determinations of a match or non-match with well-characterized confidence limits and/or error rates.

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This paper describes research and results at the National Institute of Standards and Technology (NIST) to improve the objectivity of toolmark identification through measurement of surface topography and application of unambiguous similarity metrics, such as the maximum value of the normalized cross correlation function (CCF_{MAX}). The paper builds on related efforts at NIST on ballistic toolmark identification (bullets and cartridge cases) [3]. Two types of representative tools were selected for this study: chisels for striated toolmarks and drift punches for impressed toolmarks. The consecutively manufactured chisels and drift punches were witnessed during production at Western Forge[1] (a supplier of Craftsman™ Tools). A toolmark rig was designed for the controlled generation of toolmarks. For striated toolmarks, a 2D stylus instrument was used to measure the toolmark topography. Impressed toolmark topographies were measured using a 3D disc scanning confocal microscope.

Striated Toolmarks – 2D Correlations

Striated toolmarks are created when a tool's (e.g., a chisel or screwdriver) working surface is moved across another surface. The feature of interest is the surface height profile of the toolmark in a cross section perpendicular to direction of movement or toolmark striae. A stylus instrument was used in this study to capture this height profile (**Figure 1**). The stylus has a spherical diamond tip with a radius of 2 µm (78.74 µin) which traces across the surface and records the microscopic peaks and valleys of the striation profile. The instrument has a lateral resolution of 0.125 µm (4.92 µin) and a vertical resolution of 0.8 nm (0.031 µin). Due to the slight concave edge of the chisel, only the first millimeter of the toolmark, in the direction of the striae, was complete. All measurements were performed within the first millimeter of the striated toolmark. An example of the topography data recorded can be seen in **Figure 1**.

After the toolmark profile is digitized and leveled, a filtering operation [4] is performed to reduce measurement noise and highlight toolmark features that are unique to a particular tool (individual characteristics). The measurement noise is attenuated using a Gaussian low-pass filter with a cutoff length (λ_S) of 2.5 µm. A high-pass Gaussian filter with a cutoff length (λ_L) of 0.25 mm was applied to attenuate features that are common to certain tool brands (class characteristics), features due to the form of the surface, or features due to variations in tool motion and pressure. All these features typically have

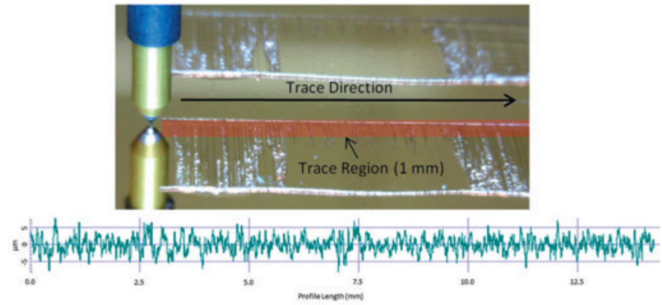

Figure 1: Stylus trace across a striated toolmark (top) and digitized topography profile of the toolmark after filtering (bottom)

components with relatively large wavelengths and amplitudes which, if not attenuated, may mask the microscopic variations in surface texture that are unique to each tool. Note that the process that generates the striations attenuates, to some extent, microscopic variations in surface texture that were present in the original surface. The filtered profile is shown at the bottom of **Figure 1**.

A mathematically objective similarity metric for two surface height profiles $Z_A(x)$ and $Z_B(x)$ is the maximum value CCF_{MAX} of the normalized cross correlation function $CCF(k)$:

$$CCF(k) = \frac{\sum_i \left(Z_A(x_i) - \bar{Z}_A\right)\cdot\left(Z_B(x_i - k) - \bar{Z}_B\right)}{\sqrt{\sum_i \left(Z_A(x_i) - \bar{Z}_A\right)^2}\cdot\sqrt{\sum_i \left(Z_B(x_i - k) - \bar{Z}_B\right)^2}}$$

Equation 1

where the summations and averages $\bar{Z}$ are performed over points common to both profiles. The variable k represents the lateral shift of the compared profile $Z_B(x)$ relative to the reference profile $Z_A(x)$. Maximizing the similarity metric $CCF(k)$ parallels what an examiner does with a comparison microscope when trying to match the patterns of two striated toolmarks. It shifts the compared toolmark profile relative to the reference profile until maximum similarity is achieved. In practice, the maximum $CCF(k)$ value is quickly calculated though a Fourier transformation of the measured profiles. The CCF_{MAX} value, in essence the normalized maximum covariance of the height profiles, varies between -1 and 1, irrespective of the bias and variance of the height data, although it is undefined for perfectly flat profiles. A CCF_{MAX} value of 1 (100 %) indicates that both surfaces are identical, except for a scale factor, whereas a CCF_{MAX} value of 0 corresponds to two random, uncorrelated surfaces. Due to the applied normalization, the CCF_{MAX} value is not affected by a different scaling factor in the compared surface heights.

1 Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

Impressed Toolmarks – 3D Correlations

Impressed toolmarks are created when a tool (e.g., a hammer or punch) impacts or presses onto a surface and leaves a negative copy of its surface topography. An impressed toolmark is three dimensional in nature and requires a 3D topography measurement tool to precisely characterize its surface topography. In this study we used a disc scanning confocal microscope [4], which allows for the quick and non-destructive acquisition of 3D surface topography. Measurements were performed with a 10X objective with a 0.30 Numerical Aperture, resulting in a lateral resolution of 3.25 µm (128 µin). Each field of view covers an area of 1.6 mm x 1.6 mm (0.063 in x 0.063 in), which was too small to measure the entire punch toolmark. A 3 x 3 grid of overlapping images was digitally “stitched together” to cover the entire punch toolmark. An example of the topography data recorded can be seen in **Figure 2**. Although the toolmark is generated by impression, the surface topography contains major striae. These striae are a negative copy of the striae on the working surface of the tool that were generated by a grinding process.

Before any correlations are performed, the edges of the measured topography are trimmed, leaving only the circular punch mark. After leveling, a Gaussian regression filter is applied to the surface data with a long cutoff length (λ_L) of 0.40 mm to attenuate waviness. A Gaussian filter with a short cutoff length (λ_S) of 40 µm is applied to attenuate instrument noise.

Similar to the comparison of surface height profiles, the maximum value $ACCF_{MAX}$ of the areal cross correlation function of two sets of surface data $Z_A(x, y)$ and $Z_B(x, y)$ is used as an objective measure of toolmark similarity:

where the summations and averages $\bar{Z}$ are performed over

$$ACCF_{MAX} = \frac{\sum_{i,j}\left(Z_A(x_i,y_j)-\bar{Z}_A\right)\cdot\left(Z_B(x_i,y_j)-\bar{Z}_B\right)}{\sqrt{\sum_{i,j}\left(Z_A(x_i,y_j)-\bar{Z}_A\right)^2}\cdot\sqrt{\sum_{i,j}\left(Z_B(x_i,y_j)-\bar{Z}_B\right)^2}}$$

Equation 2

points common to both data sets, after translating and rotating one of the data sets such that the value in **Equation 2** is maximized. An $ACCF_{MAX}$ value of 1 (100 %) indicates that both surfaces are the same, except for a scale factor, whereas an $ACCF_{MAX}$ value of 0 corresponds to two uncorrelated surfaces.

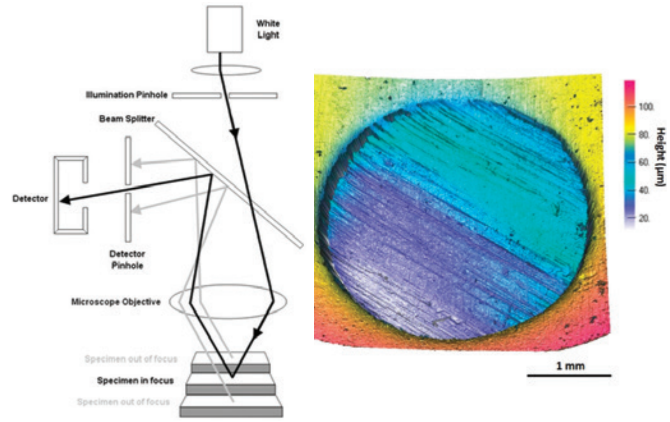

Figure 2: Principle of confocal microscopy (left) [4]; Measured surface topography of a punch toolmark (right)

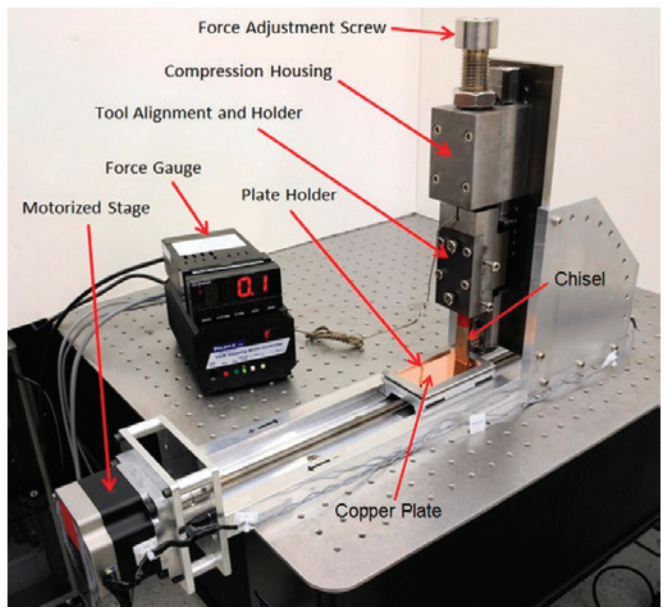

Figure 3: Toolmark rig; showing force gauge, motorized stage, compression housing, tool alignment mechanism and sample holder

Toolmark Rig

To create reproducible toolmarks, a toolmark rig (**Figure 3**) was designed to rigidly hold the tool and working surface while generating reproducible relative tool motions. All toolmarks were made on polished copper plates with a roughness average (*Ra*) of approximately 20 nm. The copper plates were polished to ensure that scratches and other miscellaneous imperfections do not interfere with the toolmarks imparted onto the plates.

To generate a striated chisel toolmark, a copper plate was mounted on a motorized stage which creates the lateral dragging motion. The rig incorporates a screw and a load cell to adjust the force exerted by the tool onto the copper sample surface. A spring and load cell connects the force adjustment screw to a piston that applies the force to the tool holder mounted on a linear rail. The spring and rail ensure that the chisel maintains a near constant force on the copper plate during motion. All chisels were mounted at 90° to the copper plate with approximately 444.82 N (100 lb) of contact force. The tool holder enables adjustment of the tool contact angles to ensure full contact with the copper plate during the dragging or punching motions or to evaluate the effect of the contact angles on the toolmarks.

By removing the load cell, spring, and force adjustment screw, the tool holder is able to freely slide along the linear rail. To create a punch toolmark, the tool holder along with the punch is dropped from a height of 170 mm (6.69 in). The whole assembly weighs 1.61 kg (3.55 lb). At the point of impact, the punch tip is traveling at an approximate speed of 1.83 m/s (6 ft/s). An anti-rebound mechanism prevents multiple hits of the surface due to bouncing of the punch after impact.

Experimental Design and Results

Each consecutively manufactured chisel was used to create two known toolmarks. The identities of the chisels were then randomized and hidden, after which two unknown toolmarks were created for each chisel. A total of 20 known and 20 unknown chisel marks were thus created. Using the CCF_{MAX} criterion described in **Equation 1**, the 20 known chisel marks were correlated against each other. **Figure 4** shows the resulting distributions of the CCF_{MAX} values for the 10 known matching sample comparisons and the 180 known non-matching sample comparisons. As the respective distributions are well separated, a minimum required CCF_{MAX} value for a matching sample pair was established as the mean of the known matching distribution minus three times the respective standard deviation. The respective critical CCF_{MAX} value was 56.4 %. This means that two samples are deemed as matching if their CCF_{MAX} value exceeds 56.4 %. The unknown chisel marks were correlated against the twenty known chisel marks, resulting in a 20 x 20 comparison matrix (**Figure 5**). Using the CCF_{MAX} criterion, each unknown chisel mark was correctly identified back to the chisel that created it.

The experimental design for the consecutively manufactured punches is similar to that of the chisels. Twenty known and twenty unknown punch marks were created using the toolmark rig. **Figure 6** shows the resulting distributions of the CCF_{MAX} values for the 10 known matching sample comparisons and the 180 known non-matching sample comparisons. The minimum CCF_{MAX} value for matching samples was calculated to be 69.31%. The twenty unknown punch marks were correlated against the twenty known punch marks, resulting in a 20 x 20 comparison matrix (**Figure 7**). Using the CCF_{MAX} criterion, each unknown punch mark was correctly identified back to the punch that created it.

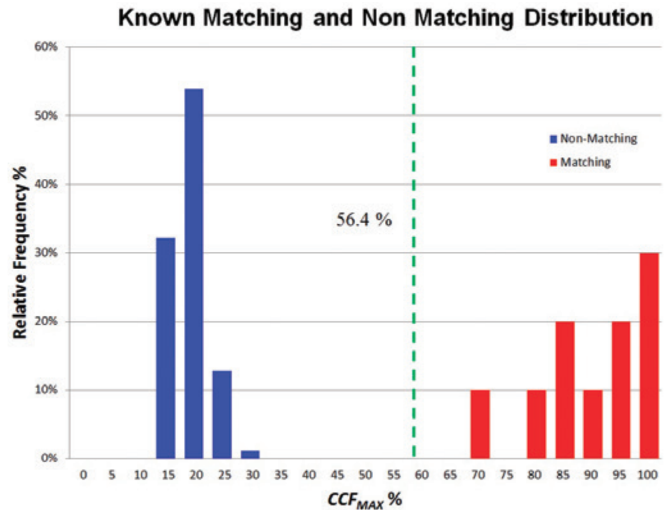

Figure 4: Distributions of known matching and known non-matching chisel toolmarks

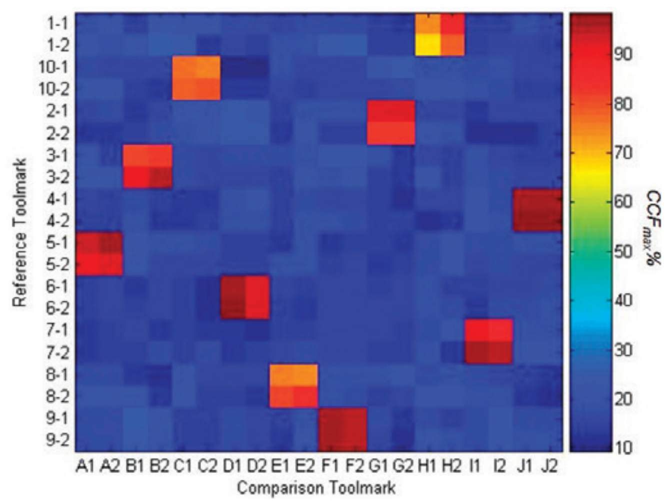

Figure 5: Correlation results for comparisons of the unknown chisel toolmarks (comparison) against the known chisel toolmarks (reference)

Conclusions

For a challenging scenario of consecutively manufactured tools using a mathematically objective metric, the maximum value of the Cross Correlation Function CCF_{MAX} applied to

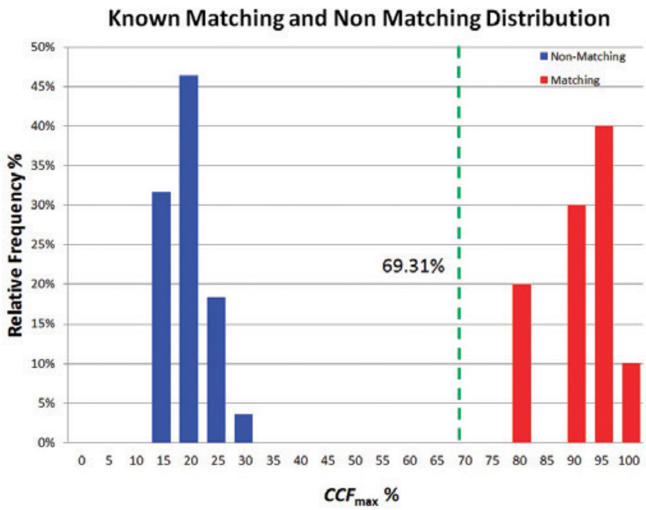

Figure 6: Distributions of known matching and known non-matching punch toolmarks

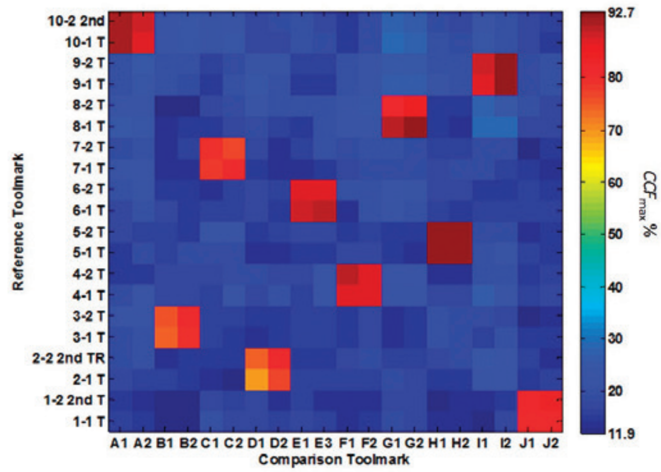

Figure 7: Correlation results for comparisons of the unknown punch toolmarks (comparison) against the known punch toolmarks (reference)

surface topography data enabled the identification of the tool that generated a particular striated or impressed toolmark. The authors describe a procedure to obtain threshold values for the CCF_{MAX} criterion for a batch of tools which can, with appropriate augmentation of the sample data set, be adjusted to include effects of non-pristine sample surfaces, manufacturing variabilities, and non-deterministic toolmark generation. The toolmark rig used in this study enables the controlled generation of toolmarks on near pristine surfaces that can serve as reference samples to which a sample found at a crime scene is compared. For the chisels, the toolmarks were made with the chisel at a 90° contact angle to the sample surface. Preliminary tests indicate that the CCF_{MAX} value degrades when a generated toolmark is compared with a toolmark generated at a contact angle that differs by more than 10° in the vertical plane of tool motion. This effect is mainly due to changes in the effective working surface of the chisel at different contact angles. Similar effects were reported in a study by Chumbley [5] involving screwdrivers. In a forensic setting, it may be necessary to generate toolmarks at different contact angles to improve identification. Further study is needed to fully characterize this effect and other potential sources of toolmark variability. The presented approach and results add support to the forensic science specialty of toolmark identification. With further research, these methods may one day contribute to a toolmark examiner's testimony in court.

Acknowledgements

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