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Automatic identification of bullet signatures based on consecutive matching striae (CMS) criteria

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ABSTRACT

The consecutive matching striae (CMS) numeric criteria for firearm and toolmark identifications have been widely accepted by forensic examiners, although there have been questions concerning its observer subjectivity and limited statistical support. In this paper, based on signal processing and extraction, a model for the automatic and objective counting of CMS is proposed. The position and shape information of the striae on the bullet land is represented by a feature profile, which is used for determining the CMS number automatically. Rapid counting of CMS number provides a basis for ballistics correlations with large databases and further statistical and probability analysis. Experimental results in this report using bullets fired from ten consecutively manufactured barrels support this developed model.

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1. Introduction

The forensic science specialty of firearm and toolmark identification in criminal investigation has more than a century of history [1]. However, it has been challenged over the years for its subjectivity and its difficulty to articulate how identification is made. Pattern matching, the traditional process for ballistics identification, is considered more qualitative than quantitative and therefore can be difficult to describe or to convince a jury or judge tasked with evaluating the examiner's conclusions.

Toolmarks produced on bullets fired through a gun barrel are primarily striated. Striae (or striations) are defined as contour variations, generally microscopic, on the surface of an object caused by a combination of force and motion where the motion is approximately parallel to the plane being marked [2]. In the 1950s, in an attempt to establish statistical foundations for firearms and toolmark identification, Biasotti conducted his original research on identification criteria [3]. In 1997, Biasotti and Murdock jointly published their quantitative criteria for identification as expressed in terms of consecutively matching striae (CMS) which means striated markings that line up exactly with one another without a break or dissimilarity in between them [4]:

(1) In three-dimensional toolmarks when at least two different groups of at least three consecutive matching striae appear in the same relative position, or one group of six consecutive matching striae are in agreement in an evidence toolmark compared to a test toolmark; and
(2) In two-dimensional toolmarks when at least two groups of at least five consecutive matching striae appear in the same relative position, or one group of eight consecutive matching striae are in agreement in an evidence toolmark compared to a test toolmark.

In the toolmark identification field, 2D striated toolmarks are those that lack discernible depth and the markings are very superficial; 3D striated toolmarks are those displaying discernible contour because the medium the toolmark is in has been displaced. According to this definition, striae appearing on fired bullets are always 3D toolmarks [2]. However, practical toolmark examination is commonly operated under an optical comparison microscope. Photographic images, instead of 3D topography are used for documenting comparisons of 3D bullet "signatures" due to historical and technical reasons. With the technical development of optical imaging instruments that have the capability of acquiring depth data, researchers began to apply this capability to automatic firearm identification systems due to its insensitivity to lighting conditions relative to conventional optical microscopy. In order to distinguish the images acquired by these instruments from the previously used photographic images, some researchers

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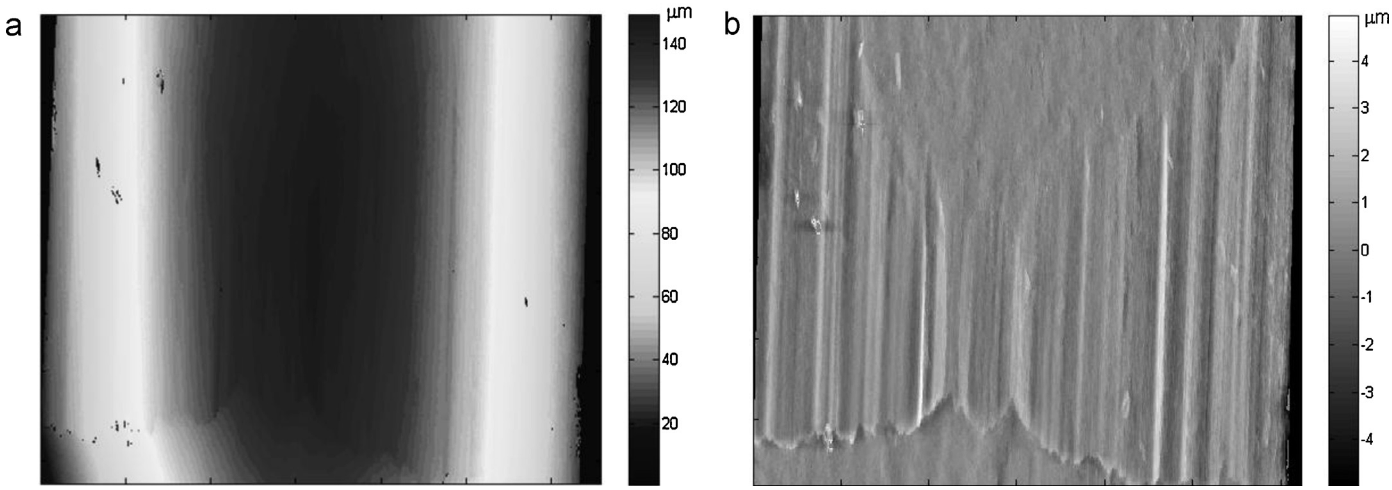

Fig. 1. Preliminary processing result for a bullet land image: (a) raw data; (b) after processing.

[5–11] and commercial product manufacturers [12–16] refer to *optical photographic images* as 2D where the value at each pixel point represents the intensity of reflected light at the point, and *topographic images* as 3D where the value at each pixel point represents its topographic height at the point.

Since the CMS criteria were established by empirical studies using manual operations and observation, Biasotti and Murdock admitted that determining the maximum number of well defined matching striae in a large statistical sample of known non-matches (KNM) was a practical impossibility. Their probability distribution of KNM striae was derived from a limited sample space. They anticipated that objective quantitative criteria for identification would eventually become established, accepted and used. Because they can quickly perform a large number of comparisons, automated systems are expected to go a long way toward establishing objective quantitative criteria and a statistical foundation for identification. By adopting Biasotti and Murdock's CMS criteria, it is practicable to make future automated systems have similar or identical measurement results to the manual method operating under a comparison microscope. The subjective procedures of examiners working with comparison microscopes could then be re-evaluated rapidly for large populations of known matches and non-matches from a variety of different calibers of bullet and cartridge types and barrel rifling manufacturing methods. The CMS criteria can then be validated or revised accordingly. These automated measurements, which are more objective, can therefore be used to increase confidence in the validity of the CMS approach [2] originally developed and practiced using direct manual comparisons.

From the early 1990s, automated identification systems for the comparison of firearms evidence have been developed and used with considerable success. However, the automated systems are still in a stage of being used as preliminary search tools in an investigation. They rank the bullets stored in the database in light of a similarity metric with respect to a subject bullet. A universally derived and statistically valid objective criterion has not yet been developed to enable automated systems to partition matching and non-matching bullets. The final decision whether two bullets were fired from the same barrel is still made by examiners using manual microscopic comparisons, and the ultimate determination of identity is therefore subjective.

A proposed automated model for objective toolmark identifications has been demonstrated by Uchiyama who developed a 2D automatic bullet comparison model in 1988, but the heights of the striations were not considered. The model was only tested using simulation rather than experiments using bullets or striated toolmarks [17].

With previous experience in automated bullet identification research using acquisition of topography images and the cross correlation score as a similarity metric [11], we try to address the aforementioned questions about statistics and subjectivity, and to provide a method for automation of CMS as the similarity metric. A computerized identification method based on 3D topography measurement and CMS criteria is described in this report. Since both the bullet features and the topography acquisition procedure are three dimensional, the bullet data enable a model to be built to fit the 3D CMS criteria. CMS values are automatically calculated from surface topography images for a set of unknown bullets compared to a set of knowns. The CMS results are compared with the true results revealed subsequently. The paper is organized as follows: a brief introduction of the CMS counting model is presented in Section 2 including image preprocessing, feature profile extraction, and striae-matching determination. The experimental results and statistical analysis are given in Section 3. In Section 4 we conclude with an evaluation of all the results.

2. Methods

The raw data of a 3D topography image of a land impression cannot be used directly for ballistics identification because the image includes components of bullet curvature, form error, noise, outliers or other unreliable data points besides the individual characteristics. Image preprocessing has to be performed to remove or attenuate these components so that the individual features of the bullet image can be analyzed. All measurements were taken with a Nanofocus µSurf[1] disk-scanning confocal microscope [18,19] which produces topography images of the surfaces. White light from a xenon bulb source enters through the objective of the microscope and illuminates the surface. The light reflects back into the objective and is directed onto a pinhole. Only the light reflected back from the current focal plane can focus through the pinhole and onto the detector. The microscope scans through a range of z-slices or focal heights during the acquisition. At the end, all the slices are compiled into a three-dimensional topography map. The measurement uses an objective lens with 20× magnification. The nominal pixel spacing is 1.5625 µm in both x- and y-directions, and the nominal z-slice interval is 0.15 µm. The preliminary image processing primarily includes: (1) identifying and removing dropouts and outliers, and replacing these points with interpolated data; (2) applying a band pass filter to remove low frequency curvature, form error and high frequency noise. Fig. 1 shows an example of a 3D bullet topography image with its processed results. The criteria for identifying outliers and dropouts are based on

[1] Certain commercial equipment, instruments, or materials are identified in this paper to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

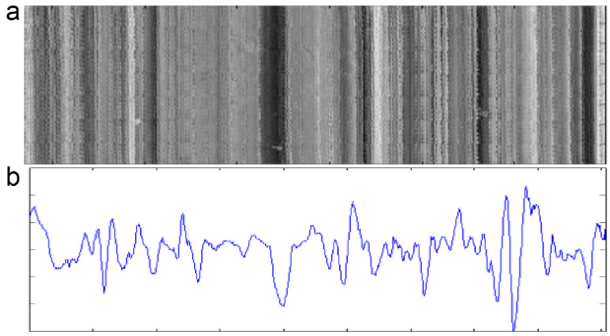

Fig. 2. NIST SRM 2460 standard bullet (a) processed land image; (b) a cross section profile.

previous acquisition and measurement experience [11]. The band pass filter is a standard Gaussian filter [20] with limits of 250 and 15 μm.

During an actual bullet identification procedure using a comparison microscope, the examiner rotates and moves the pair of bullets to find areas on each bullet surface with striae marks having sufficient agreement to fulfill and possibly exceed the subjective sufficiency of similarity for identification. The examiner then may employ the CMS criteria for a quantitative measure of identification.

In an ideal situation, the barrel engraves consistent striation marks along the whole length and width of the land impression of the bullet. The positions and shape of striae can be reproduced in the peaks and valleys of a single topography profile. So any single profile can potentially be used for a land impression comparison. An example of this quality of land engraving is found on the NIST Standard Reference Material (SRM) 2460 standard bullet, which is manufactured by a numerically controlled (NC) diamond turning process [21]. Fig. 2 shows one land image of a standard bullet and one of its cross section profiles. In this case the CMS counting model can be developed based on profile comparison.

However, for bullets that have been fired from a gun barrel, informative and consistent striation marks are not necessarily impressed on the whole land impression area of the bullet. Some areas are weakly or inconsistently striated by the barrel and cannot provide helpful information for bullet identification. Such areas can be found in Fig. 1(b). Generally, automatic identification systems for bullets create a feature profile by averaging multiple cross section profiles [5,7,10,11] instead of using a single section, thus attenuating the effects of random errors. Optimal feature profiles and higher bullet identification accuracy should also be achieved if those areas that do not contain valid striation information are excluded through certain processing before the averaging is calculated. An edge detection technique has been adopted to locate valid striation marks. By applying the edge detection technique, the positions of the valid striation marks can be located. Skid marks can also be distinguished from real striae by virtue of their different tilt angles and can be eliminated. For more technical details refer to [22]. Fig. 3(a) shows the extracted striae from the topography image in Fig. 1(b) using the edge detection technique. By expanding the edge points of each valid stria with a reasonable width and superimposing these striated areas on the original topography image, valid correlation areas can be identified and invalid correlation areas masked out as shown in Fig. 3(b).

In order to calculate the compressed average profile, the land image has to be rotated to make the striae upright. That requires an accurate and automatic calculation of the twist angle of the land image. Each individual stria edge curve shown in Fig. 3(a) can be separated by applying a mathematical morphology method [23] and fitted to a straight line from which the tilt angle can be automatically calculated. Theoretically all striae should have the same tilt angle caused by the twist of the barrel rifling. But in practice they vary over a small angular range due to imaging error. An accurate value for the overall tilt angle is calculated by averaging the angles obtained from a number of striae edge curves [22].

By rotating the masked land image and then averaging all valid sections of profiles along the direction of the striae, the extracted feature profile is generated. The resulting profile is plotted in Fig. 4. Since all areas that have not been adequately engraved by the barrel features are removed from the acquired image, the resulting topography of the striae along the cross section direction is faithfully represented by the shape of the feature profile. The striae in a 3D image have been converted into the valleys and peaks in a 2D profile. Note that the points of the feature profile result from averaging different numbers of data points along the striae depending on where the valid and invalid areas are located.

When firearm examiners compare striated toolmarks for a possible identification, they compare intensity, height and depth, width, curvature and spatial relationship of the individual peaks, ridges and furrows [24]. An automatic CMS number counting model is established here based on this procedure with some simplification. In this model, a stria mark is represented by its position, width and height. In Fig. 4, P stands for the position of the peak; W stands for the width of the stria and H stands for the height of the stria, which includes left height H_L and right height H_R. A parameter for the curvature is not defined here because of its difficulty in extraction and comparison. When all these factors for a pair of stria in two compared lands are in a tolerable range, they are considered to be "matched". As discussed above, before the CMS number is counted, a Gaussian low pass filter is applied during the image processing in order to remove high frequency electrical noise and closely spaced minor striae, which are not considered to be valid striae. After different values were tested, the short wavelength cutoff was chosen to be 15 μm. Attenuating structures finer than this scale tends to produce more accurate and stable CMS results. Note that the selected tolerable range and cutoff length may be variable depending on the pistol brands which present different morphological characteristics. In this experiment, these parameters are optimized based on tests of bullets fired from Ruger pistols. Research on bullets fired from other brands of pistols will be needed to further support or refine these parameter settings.

3. Experiment and results

In order to validate the developed model, a test set of bullets fired from ten consecutively rifled 9 mm Ruger pistol barrels were compared using a program based on this model. Each test set included a control set and an unknown set of bullets. The control set was comprised of bullet pairs from each of the ten barrels. An unknown set of 15 bullets was comprised of at least one bullet from each barrel and no more than three bullets from any one barrel. A total of 240 such test sets had been prepared and distributed worldwide in a large study conducted by Hamby and Brundage. A detailed description of the test motivation and the selected barrels and ammunition can be found in Ref. [25].

We implemented the procedure first for the 20 bullets. Statistical results for all known non-matching and matching land comparisons are shown in Tables 1 and 2, respectively. The set of known non-matches consists of 20 bullets × 6 lands × 18 non-matching bullets × 6 lands = 12,960 comparisons (A vs. B and B vs. A are counted as two comparisons because the results occasionally show slight differences). Of all 12,960 land-comparison results, no

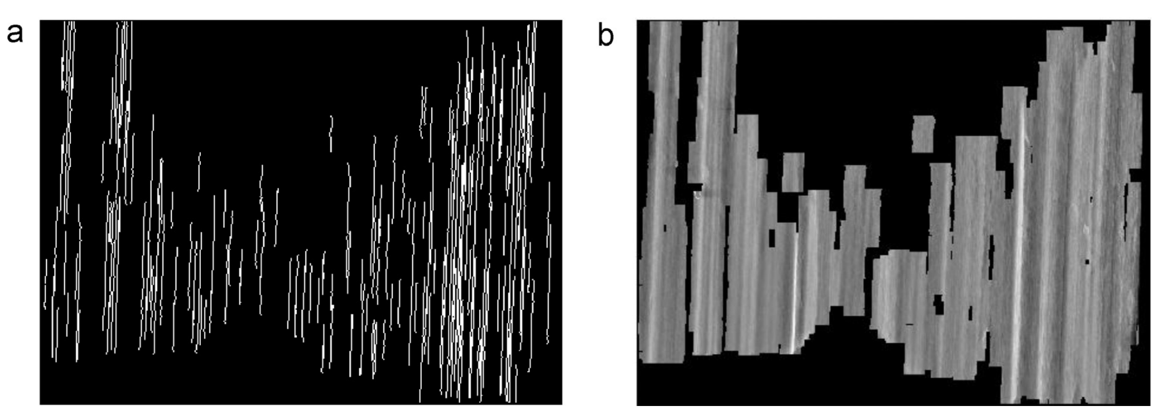

Fig. 3. Image masking. (a) Edge detection result; (b) masked land image.

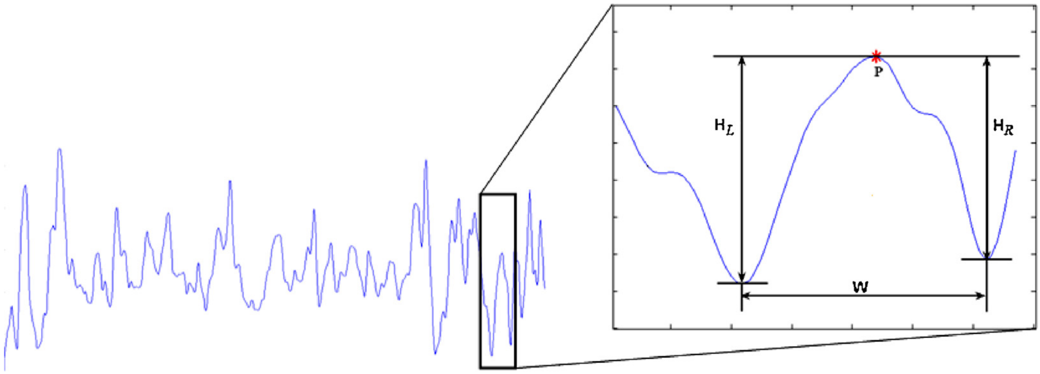

Fig. 4. Model for striae matching identification. Each stria is specified with a width W and two peak-valley heights, H_L and H_R.

Table 1
CMS results for known non-matches (total 12,960 land comparisons).

3D CMS	Amount	Proportion (%)
0	3 887	29.99
1	8 219	63.42
2	782	6.03
3	70	0.54
4	2	0.02
≥5	0	0

result was found that meets the CMS criteria including the H, P, and W topography tolerances described above.

The known matching set consists of 10 pairs of bullets and 60 matching land comparisons. Using the 3D CMS criteria, all 10 pairs of bullets fired from same gun barrel were successfully identified. Out of the 60 pairs of individual matching land images, 29 pairs or about 48% were identified (Using criteria of 6 CMS or two groups of 3 CMS).

These tests for the known matching and known non-matching bullets demonstrated the validity of the model. Then the model was applied to the 15 "unknown" bullets. Before these experiments, the operator did not obtain any barrel source information about these bullets, and therefore this phase of the testing was "blind". Each of these 15 unknown bullets should match the two bullets in the control set that are fired from same barrel. Out of a total of 30 matching pairs, 29 are correctly identified; with one matching pair missed. Similar statistical results are obtained in comparison with the previous results of 10 pairs of known matching bullets that are shown in Table 2. Out of a total of 180 matching land comparisons, 93 pairs (about 52%) are identified.

Fig. 5 shows a portion of an identified matching pair land surface. Six consecutive matching striae are identified as the vertical lines indicate. During the automated striae counting, striae pair I is not considered valid due to their small left-side amplitudes (H_L), while striae pair II is not counted because the height difference is beyond a preset threshold. The right hand heights H_R of the two striae there do not match because the clear valley in the red curve corresponds to a shoulder in the blue curve. The corresponding image under a comparison microscope is also shown for reference. In this figure, the blue profile corresponds to the lower land image and the red profile corresponds to the upper land image. The bullet nose is toward the top.

Table 3 lists the statistical CMS results of all matching lands in the blind comparisons. In addition, out of 9 720 possible non-matching lands (15 test bullets × 6 lands × 18 non-matching bullets × 6 lands) not one unknown land was misidentified (false positive) as matching a control land.

According to the CMS model, two bullets can be considered to be fired from the same barrel if any single land comparison result meets the CMS criteria. If we conduct a statistical analysis in a sample space with assumptions that: (1) the probability of correctly identifying a matching land is rounded to 0.48 (approx. 29/60); and (2) each bullet has six lands; then the probability of a missed identification is $(1–0.48)^6 = 1.98\%$. This means a possible

Table 2
CMS results for known matches (total 60 land comparisons).

3D CMS	Amount	Proportion (%)
≤2	16	26.67
3	5	8.33
4	6	10
5	4	6.67
Meet CMS criteria	29	48.33

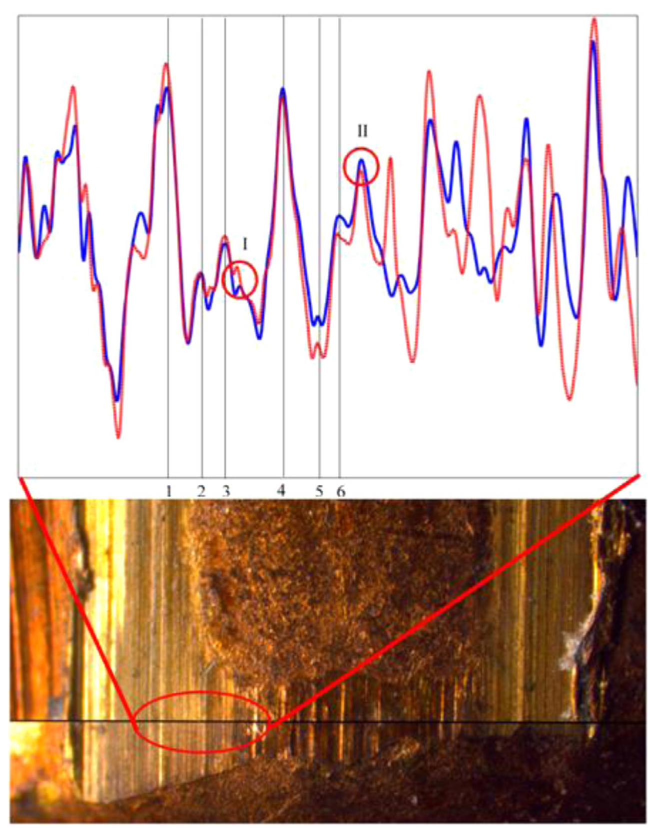

Fig. 5. Example of an identified match between one of the unknown bullets and one of the control bullets.

Table 3
CMS results for matches in the blind comparisons (total 180 land comparisons).

CMS	Amount	Proportion (%)
≤2	36	20
3	21	11.67
4	16	8.89
5	14	7.78
Meet CMS criteria	93	51.67

missed identification for about every 50 correct bullet comparisons. Even if this is acceptable, a lower missed identification rate is still desired. A potential approach to improve the accuracy by considering all six lands of a bullet as one wide land is under investigation theoretically and statistically.

4. Conclusion

Although Biasotti's CMS quantitative identification criteria are becoming widely accepted by firearm examiners, the procedure still has subjective elements and lacks a more comprehensive statistical proof. The significant points of the present study on the CMS based automatic bullet identification model are summarized as follows. First, the model fills the gap between manual operation and automated systems. It makes the computerized database search system capable of completely implementing the identification task rather than simply giving a priority order for further manual operations. Second, it increases the objectivity of firearm identification examination. In traditional operations using a comparison microscope, due to the subjectivity in defining a striation pattern on the bullet surface, two firearm examiners may draw different conclusions as to whether two bullets match. With the analysis method model described here, the CMS number can be obtained independent of firearm examiners or different comparison microscopes types. Third, the model lays solid groundwork for future statistical analysis. When the classic CMS criteria were proposed, statistical analysis for a much larger database was nearly impossible because it was based on empirical and manual experiments. The rapid processing speed of a computerized CMS counting system makes statistical analysis for a very large database possible so that the CMS criteria have the possibility of obtaining more theoretical and statistical support and ultimately becoming a scientifically validated objective bullet identification standard.

This experiment using bullets fired from 10 consecutively manufactured barrels helps to validate the model because bullets fired from such a set of barrels are produced by the same tool. Therefore, it should be more difficult to differentiate individual units among such a set of barrels than among a set of barrels chosen randomly, even from a single manufacturer. Consecutively manufactured barrels could have a strong set of matching subclass characteristics that could potentially lead automated software to false positive identifications. However, no false positives were produced in this automated CMS study.

Even though the database used in this study was limited and was obtained from a specified type of firearm, it is practical to extend the method to a large database. Presently there are differences between the model presented here and actually applied CMS criteria, even though the model is built to simulate the CMS criteria. The methods are not identical because the CMS criteria were proposed for manual operations with optical microscopy, whereas the model employs 3D topography data. So far the thresholds for height and width parameters in the model are determined empirically. Obtaining optimized parameters may need further theoretical and experimental study. However, the present results have provided a fairly objective test and have demonstrated support for the CMS criteria for identification.

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