

# Persistence and Variability of Cartridge Case-Firearm fingerprint

Komal Yadav<sup>1</sup>, Priyanka Negi<sup>1</sup>, Shivam Verma<sup>1</sup>, Soojal Saryal<sup>1</sup>, Aishwarya Baunthiyal<sup>1</sup>, Paras Sharma<sup>1</sup>,  
Amrita rai<sup>1</sup>, Kritima kumari<sup>1</sup>

<sup>1</sup>Department of Forensic Science, School of Basic and Applied Sciences, K.R. Mangalam University, Gurugram, India

Corresponding author: - Priyanka Negi, priyankasoni.negi@gmail.com

## Abstract

Forensic firearm examination relies on microscopic toolmarks present on fired cartridge cases for firearm comparison and identification. Repeated firing can cause wear or modification of firearm components that produce cartridge-case toolmarks, which may alter the morphology and persistence of breech-face and firing pin impressions over repeated firing. Some individual characteristics may remain reproducible across multiple firings. Microscopic tool marks can examine using three-dimensional surface topography, quantitative feature extraction, and automated comparison methods. These approaches can be used to evaluate three-dimensional surface characteristics and assess the reproducibility of toolmarks. During repeated test firings, cartridge cases may exhibit variations in toolmark patterns. These variations can be used to determine whether cartridge-case markings could still be reliably associated with the source firearm in a database. Repeated test firings can also be used to characterize sources of toolmark variability. Standardized three-dimensional data acquisition remains critical for validating the persistence of these markings across diverse ammunition types. However, the implementation of such approaches should be supported by studies that have validated their accuracy and reliability. Although there have been technological advancements, issues have remained with respect to image resolution, database size, and standardization of protocol for different types of guns and ammunition. The aim of this paper is to study the influence of cartridge case metallography on the variations that can be seen in breech face and firing pin impressions, so as to differentiate between real mechanical wear and temporary obscuration, such as fouling or debris buildup. This avoids false exclusions in casework involving heavily fired firearms, by setting persistence limits that signal the duration for which individual tool marks remain identifiable, before algorithmic matching starts to fail. *No two firearms are microscopically alike*

**Key Words-** Microscopic tool marks, Cartridge case, tool marks variability, surface tomography, Breech face

**1. How to cite this article:** Komal Yadav<sup>1</sup> Priyanka Negi<sup>1</sup> Shivam Verma<sup>1</sup> Soojal Saryal<sup>1</sup> Aishwarya Baunthiyal<sup>1</sup> Paras Sharma<sup>1</sup> Amrita rai<sup>1</sup> Kritima kumari<sup>1</sup>. Persistence and Variability of Cartridge Case-Firearm fingerprint. Int J Drug Deliv Technol. 2026;16(85s):657-665. DOI: 10.25258/ijddt.16.85s.64.

## Introduction

Forensic firearm examination is an important part of criminal investigations. This is because it can provide scientific evidence linking fired ammunition to a particular firearm. When a gun is fired, the cartridge case comes into contact with several components, including the breech face, firing pin, extractor, and ejector. These components leave microscopic toolmarks on the cartridge case, which may contain both class and individual characteristics (Franklin & Morris, 2025; Gambino et al., 2011; Riva et al., 2020.; Weller et al., 2012). The examination of these marks can provide useful information about whether cartridge cases were fired from the same firearm. However, the marks produced by a firearm are not exactly identical with every shot. Repeated firing can cause mechanical wear, surface changes, fouling, and the accumulation of debris on firearm components, which may affect the appearance of breech-face and firing-pin impressions (Algül & Yalçın Sarıbey, 2026; Kirk et al., 2017; Manzalini et al., 2020; Ott, Soons, et al., 2017). Due to which slight variations can occur between cartridge cases fired from the same firearm. Despite these changes, some characteristic features may remain sufficiently

stable and reproducible over repeated firings to retain their value in firearm examination.



**(B)** Fig 1- (A) close ups of toolmarks. (B) different toolmarks of the cartridge cases in every aspect. (Xin et al., 2026)

By examining 200 consecutive test fires from each of 24 new Ruger SR9 9 mm pistols using the IBIS® Heritage™ system. It was observed that some differences in breech-face and firing-pin marks between firings. However, the results did not show an overall decrease in the system's ability to compare the cartridge cases as the number of shots increased.

This suggests that although repeated firing can cause some variation in the marks, the variation does not necessarily make comparison impossible (Kirk et al. 2017(Basu et al., 2022; Kirk et al., 2017)

A firearm was examined over 3,070 consecutive firings. The similarity between cartridge cases varied slightly throughout the firing sequence, but the characteristic marks produced by the firearm remained consistent enough for the Evofinder® system to correctly associate the known cartridge cases. It was also observed that cartridge cases fired closer together in the sequence generally showed greater similarity. These findings indicate that some variation in toolmarks is normal even when cartridge cases are fired from the same firearm, while characteristic features may still remain sufficiently consistent to indicate a common source (Zhang et al. 2017; Soons et al., 2017)

The firearm represents a tool that transfers marks onto bullets and cartridge cases (Franklin & Morris, 2024a; Le Bouthillier et al., 2023). It is therefore important to distinguish genuine changes from temporary changes caused by fouling or debris so as to avoid erroneous exclusions during forensic comparison. Forensic tool mark identification includes firearms identification, an area of tool mark investigation that specializes in identifying different firearms and parts (Kumar et al., 2021; Mattijssen et al., 2023; Mattijssen & Kerkhoff, 2026; Read *“Reference Manual on Scientific Evidence: Third Edition”* at NAP.Edu, n.d.).

The studies reviewed show that cartridge-case toolmarks are neither completely fixed nor completely unpredictable (Guyl et al., 2023; Soons et al., 2017b). Marks produced by the same firearm can change slightly with repeated firing, but some characteristic features may remain stable enough to help associate cartridge cases with a common firearm. At the same time, the condition and firing history of the firearm, along with factors related to ammunition, can influence the appearance of these marks. This makes it important to understand the reason behind the observed variation rather than assuming that every difference represents a change in the firearm. (Ott, Soons, et al., 2017; Williams et al., 2024)

Recent developments in forensic firearm examination have included the use of three-dimensional surface topography, quantitative feature extraction and automated comparison algorithms (Baiker-Sørensen et al., 2023a; Basu et al., 2022b; Liu et al., 2024; Senin et al., 2006; Song et al., 2012; Xin et al., 2026b). These techniques provide objective means of documenting and evaluating microscopic surface characteristics of cartridge cases. Three-dimensional measurements can help assess reproducibility of toolmarks across repeated firings and whether characteristic features remain stable enough to be accurately related to a

source firearm. (“Zheng et al. (2020) NIST.; Vorburger et al., 2016)

Database based approaches can further help in evaluating the variability of toolmarks across various cartridge cases, guns and types of ammunition. (Zheng et al., 2020)

Despite these technological advances, there remain challenges connected to image resolution, database size, variability in ammunition, and standardization of data-acquisition and comparing protocols (Alsdurf et al., 2025)

Variations in the markings of the cartridge case may be due to differences in the condition of the firearm, the nature of the production, the composition of the ammunition and the number of previous firings. Hence, it is necessary to carefully evaluate the persistence of toolmarks to determine how long individual characteristics are identifiable as a firearm is repeatedly used. The present review focuses on the persistence and variability of cartridge-case toolmarks produced by the same firearm, with a particular focus on breech-face and firing-pin impressions. It examines the effects of repeated firing, cartridge-case metallography, mechanical wear, fouling, and debris accumulation on tool mark morphology as in glock pistol. The review focuses on using of three-dimensional imaging and automated comparison techniques for the test of toolmark reproducibility and firearm association based on database. Knowledge of these factors can help to establish scientifically valid persistence limits and standardized practices for the examination of firearms, improving the reliability and interpretation of cartridge-case evidence in forensic investigations. Zheng et al. (2020) NIST,” 2016; Ott, Soons, et al., 2017; Zheng et al., 2020)

## 2. Literature review

### 2.1 Findings

Every mark at the microscopic level is different, if it was shot by the same fire arm then also some parts on microscopic level will be different. No two firearms are microscopically alike. The manufacturing process of a firearm can leave unique features on the bore, firing pin, breech face and many other firearm components, when firing a round, these features are transferred to the bullets and cartridge cases, producing distinguishable individual marks that can be used to make examination (Zhang, K., & Luo, Y. 2018; Mookiah et al., 2025)). The pressure of gases on firing the cartridge may alter the firearm marks according to the amount of pressure exerts by the propellants, the rapid pressure increase forces the bullet out of the cartridge case and out of the barrel of the firearm. As the bullet is traveling down the barrel, the gas pressure is also pushing the cartridge case back up against the breech face of the firearm, resulting in the breech face impression (Kirk, J. N., Law, E. F., & Morris, K. B. 2017, Kirk, J. 2015). These marks are found as striations on the bullet imparted by the

rifling of the barrel and as striations and impressions left on the surface of the cartridge case during the firing sequence (Ott, D., Soons, J., Thompson, R., & Song, J. 2017). For identifying and comparison different types of software can be used to evaluate the test samples which can be in bulk. The Integrated Ballistics Identification System (IBIS®) is one such system that was established in the early 1990s at the request of the Bureau of Alcohol, Tobacco, Firearms, and Explosives (ATF) (Morris, Keith B., et al 2017).

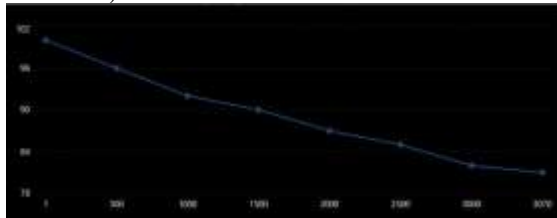


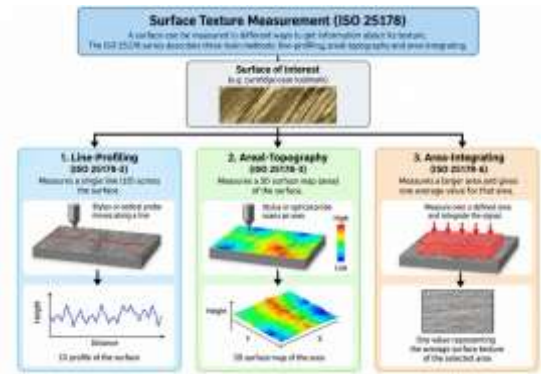
Fig no. 2- Variation of Cartridge-Case Tool marks Over 3,070 Consecutive Firings: Cartridge cases fired closer together showed greater similarity, while tool mark characteristics changed slightly across repeated firings. (Zhang, K., & Luo, Y. 2018).

Variety of similarity of toolmarks on cartridge case are seen decreasing on decreasing the number of shots per time as can see in the graph

Automated search and retrieval systems were developed for general cartridge case and bullet comparison, and may also be useful for case linkages when no firearm is present (Morris, Keith B., et al 2017). In order to identify the firearm efficiently, an automatic identification system is indeed much needed to narrow down the possible number of matching required quickly (Ghani, N. A. M., Liong, C. Y., & Jemain, A. A. 2010)

## 2.2 Identification in 2d and 3d

Tool marks are permanent changes in topography or impressions formed on a surface when it comes into forceful contact with a harder object or tool. These marks reflect the shape and characteristics of the tool involved; it may modify the both 2D and 3D shape of the cartridge cases. Striation signatures (2D profile tool marks) on a bullet are caused by its passage through the gun barrel, Impression signatures (3D topography tool marks) on a cartridge case are caused by impact with the firing pin, breech face and ejector. Similarities also can be determined. (Vorburger, T. V., Song, J., & Petraco, N. 2016; (Meral & Akyüz, 2026a; Stocker, n.d.; Suresh, 2017).



A number of different methods have been developed to measure surface topography. They may first be classified into three categories—line-profiling, areal-topography, and area integrating—as described in an ISO standard (Vorburger, T. V., Song, J., & Petraco, N. 2016 (Wen et al., 2023).

Figure 5- Techniques to determine surface texture of cartridge cases (Vorburger, Theodore V., J. Song, and N. Petraco 2016).

A high-resolution probe or sensor tracks across a single straight path on a surface. It records data along a single lateral axis (x), measuring the vertical variations (z). This method extends coordinate scanning into three dimensions (x, y) and (z) over a defined surface field. This is achieved either by sweeping a single probe through multiple adjacent, parallel lines or by using 2D optical sensors (like cameras) to capture a whole section simultaneously. Unlike the previous two methods, area-integrating techniques do not measure explicit coordinates (x, y) or generate line/map graphs. Instead, they bounce energy (such as light or compressed air) across a large, representative area of the surface all at once. The surface irregularities alter the way that energy reflects or flows (Gerules et al., 2013)

## 2.3 Metallurgy

The difference in the material of the cartridge case as well as primer cap can contribute to the identification to the firearm fingerprint, the cartridge case are made of the generally brass and steel, aluminium, nickel-plated brass, or plastic, and the primer is made of cartridge brass, copper, gilding metal, or occasionally steel. Differences in primer-cap material and hardness can influence firing-pin impression topography and may affect the performance of correlation methods used for ballistic toolmark comparison. (Addinall, Katie, et al 2019 (Chen et al., 2025).

This found that, although both sample types could be described as brass cased, Berdan primed. 308 Winchester ammunition, there were differences observed to the type of propellant, projectile mass and projectile design between the two brands (Meral & Akyüz, 2026)

It can therefore be concluded that the production of ballistic tool marks upon the cartridge's primer

occurs in two defined stages: an impression stage (resultant of the firing pin strike), and an extrusion stage (resultant of a surplus in the backpressure produced by the combustion of the propellant following primer ignition and the primer's subsequent ejection from the cartridge primer pocket into the bolt face). (Williams, M., Addinall, K., & Blunt, L. 2024)

Figure6- types of material used to manufacture the cartridge cases and can show different effects(Williams, M., Addinall, K., & Blunt, L. 2024)

### 3. Critical Discussion

Cartridge cases can exhibit characteristic marks made by components of the firearm, like the firing pin, breech face, extractor and ejector. These marks are used to try to determine if cartridge cases came from the same firearm. But research shows that these markings are not uniform across all firings. Instead, they have a mix of persistent features with natural variability. This distinction is important as the marks must be sufficiently stable such that identification remains possible, whilst at the same time they must be evaluated with knowledge of the changes that occur as a consequence of repeated firing and firearm wear. (Algül & Yalçın Sarıbey, 2026; Ott, Soons, et al., 2017)

**3.1 Persistence of firearm marks** This is one of the strongest pieces of evidence for persistence, five firearms for 3,070 consecutive firings each. They found that breech-face marks and firing-pin impressions changed incrementally throughout the firing sequence. Cases fired in close succession tended to be more similar than cases that were separated by a larger number of firings. Although variation was observed, within-firearm variation was lower than between-firearm variation and the Evofinder® system was able to correctly match nearly all known same-firearm specimens. (Zhang & Luo, 2018)

#### Strengths:

The major strength of this research is the very large number of consecutive firings. The studies of 3,070 shots give much stronger evidence of persistence than those based on a few test fires. Weaknesses: The study was based on a certain type of firearms and an automatic correlation system. Therefore, the results cannot be automatically extrapolated to all types of firearms, calibers, types of ammunition or different examination conditions.

**3.2 Variation in the same firearm** The number of test fires required to represent the variability of marks produced by one firearm. They used 30 9 mm Luger guns with approximately 100 cartridge cases per gun and concluded that two test fires were not enough to adequately represent the distribution of breech-face and firing-pin marks.

Their statistical analysis showed that a minimum of 15 cartridge cases were required to represent the match distribution with greater than 80% equivalence, while approximately 30 cases provided a more conservative representation.(Law et al., 2017; Tong et al., 2019)

It is important to note this because it shows that variability is a normal phenomenon in cartridge cases from the same source. If the examiner studies only one or two test firings, he/she will not have an opportunity to examine all possible markings made by the firearm.

#### Strength:

This paper has applied a statistical method of analysis rather than using purely visual observations. Weakness:

This research was originally conducted on 9 mm Luger firearms and IBIS® correlation scores, thus it is not universal for all calibers and mechanisms.

### 3.3 Variability for different calibres

The scope of their research on different calibres and guns. Once more, they found that the amount of cartridges required in order to provide an adequate variability exceeded the minimum amount of test fire used traditionally by two times. The amount of 15 cartridges was enough to ensure the probability of 80% in representing the whole match distribution, and about 25 were enough for full representation.(Law et al., 2017)

#### Strength:

The existence of several different calibre sizes and weapon types adds weight to the point that variability should be examined more broadly, not as a feature of one particular weapon.

#### Weakness:

Since the study is mainly concerned with IBIS® correlation scores, the results apply only to how similarity scores are represented, and do not address all of the physical factors involved in causing variations in toolmarks.

### 3.4 Effect of extensive firearm firing

Additional research demonstrates that the effect of persistence might eventually include the effect of firearm wear. In 2026, a study was conducted using 15,000 consecutive shots fired from a 9 mm Parabellum pistol with cartridge cases collected during various stages of firing. Structural changes were noticed in the firing pin impressions, and alterations were detected after about 3,600 rounds. The deformation resulted in change in the structure of the impressions.(Algül & Yalçın Sarıbey, 2026) It is especially important in the case of your research because it proves that the notion of persistence should not be associated with permanence. In this way, even if a gun produces marks that are sufficiently persistent during a certain time period,

extended usage of it could change its surface, thus affecting the marks it leaves on cartridge cases.

#### Strengths:

The number of fired shots is really large and makes 15,000, which makes this paper valuable when investigating long-term effects and wear of firearms.

#### Weaknesses:

The experiment was conducted using only one 9 mm pistol, which means that the point of changes observed should not be seen as universal threshold for all firearms.

Figure7- The figure illustrates that cartridge-case toolmarks are not completely identical after every firing, this is an estimation(Soons et al., 2017)

#### 4. Research Gap

Although previous studies have established that breech-face marks, firing-pin impressions, ejector and extractor marks, primer impressions, and other cartridge-case features can contain persistent and characteristic information, there is a need to understand how such marks vary within the same firearm with repeated firing and how such variation should be considered typical; studies involving consecutive firings, including work using IBIS®, Evofinder®, and large firing sequences, have shown that toolmarks can vary with use, but the relationship between physical changes in the firearm, ammunition and primer manufacturing tolerances, fouling, cleaning, mechanical wear, and comparison scores has not been established(Alsdurf et al., 2025; Baiker-Sørensen et al., 2023; Manzalini et al., 2020; Williams et al., 2024).

It is not clear whether there are identifiable stages or thresholds at which changes in the breech face or firing pin become significant to automated or examiner-based identification, and although research has examined how many test fires are necessary to represent within-firearm variability, more work is needed across a range of firearm types, manufacturers, calibres, ammunition, and conditions to determine whether any one sampling strategy can represent the variability of an individual firearm, and the literature on persistent and characteristic features leaves a need for more objective ways to distinguish firearm-specific marks from temporary, manufacturing-, ammunition-, or randomly occurring features; research into 3D topography, similarity measurements, geometric features, image-processing techniques, and automated database-search algorithms has demonstrated considerable potential(Guyll et al., 2023; Law et al., 2018b; Mattijssen et al., 2021; Md Ghani et al., 2010; Xin et al., 2026c)

But a need remains to determine which surface features are most stable, reproducible, and discriminating under realistic casework conditions, and how differences in imaging equipment, measurement resolution, cartridge-case condition, and data-processing methods impact such results, and other 3D or image-based approaches need

further independent validation on larger and more diverse data sets (including repeated firings, different firearm makes/models, different ammunition and primer materials, damaged or poorly marked cases, and firearms exhibiting different levels of wear), and the development of likelihood-ratio approaches and quantitative comparison scores has improved the possibility of expressing evidential strength numerically, but additional research is needed to establish appropriate statistical models, error rates, score distributions, decision thresholds, and population-relevant databases to provide reliable interpretation and not just similarity indicators; work on examiner accuracy, repeatability, reproducibility, and the use of AFTE conclusions has demonstrated that human interpretation can vary, leaving a need to understand the sources of examiner disagreement and develop methods that improve consistency without removing the role of expert judgment; the research on cartridge-case manufacturing and primer production shows that manufacturing tolerances can influence the marks produced with firing, but more controlled studies are needed to separate manufacturing variation from firearm characteristics, and determine how primer-cap material, cartridge construction, and manufacturing processes influence the persistence and reproducibility of toolmarks; and studies of breech-face manufacturing suggest that the manufacturing process itself can contribute to the observed characteristics, but the connection between manufacturing method, microscopic surface topography, subsequent wear, and resulting marks on fired cases remains unclear(Baldwin et al., 2023; Basu et al., 2022c; Franklin & Morris, 2024b; Geradts et al., 2001; Monson et al., 2023; Ott, Thompson, et al., 2017; Soons et al., 2017d; Vorburger et al., 2015; Williams et al., 2024c)

#### 4. Future Direction

Future research on the persistence and variability of cartridge case-firearm fingerprints should be devoted to elucidating the mechanisms by which microscopic toolmarks are formed, retained, and modified during repeated firings of a given firearm. Longitudinal experimental studies should be conducted to establish whether breech-face impressions, firing-pin impressions, ejector marks, extractor marks, and other characteristic features are retained or gradually modified as a given firearm undergoes wear. Such studies should explore the effects of different ammunition, primer materials, cartridge-case manufacturing differences, and differences in cartridge-case hardness, among other variables, on the formation and persistence of toolmarks.

An additional priority area in future research is the increased utilization of three-dimensional surface topography and quantitative feature analysis. Future studies should move beyond the use of primarily 2D comparisons and begin to explore the potential of

utilizing 3D measurements to characterize the depth, orientation, geometry, and distribution of microscopic marks. Such an approach has the potential to facilitate the discrimination between persistent, firearm-specific characteristics and inconsistently formed features. The establishment of large reference databases of cartridge cases from multiple firearms, multiple ammunition, and multiple firing sequences and operating conditions would enhance the ability to evaluate the persistence and variability of individual characteristics while supporting the development and testing of automated comparison systems and statistical methodologies.

## 5. Conclusion

The presented research shows that cartridge case–firearm fingerprints are a valuable source of evidence because of the toolmarks produced on them by breech face, firing pin, extractor and Ejector during discharge. The reviewed articles confirm the possibility of distinguishing two types of the reviewed literature indicates that cartridge-case toolmarks exhibit both persistent and variable components. Some features show substantial reproducibility, whereas others vary with firearm condition, ammunition, fouling, manufacturing variation and wear due to their inconstancy, the former can serve as a basis for identification. The research results presented in the articles show that breech-face and firing-pin marks can change gradually during repeated firings as a result of mechanical wear or dirt buildup but retain enough similarity to be used for identification. At the same time, the within-firearm variability is lower than between-firearm variability, which also contributes to the identification potential of breech-face and firing-pin marks. The reviewed articles also highlight the importance of considering factors related to ammunition when studying toolmarks, such as the properties of the metal of the cartridge case, the quality of the primer, allowable dimensions of the manufacturer, the pressure of the charge. These factors, together with cartridge-case and primer hardness, firearm-surface characteristics, and manufacturing tolerances, can influence the morphology and reproducibility of toolmarks. These factors, along with the characteristics of the barrel, firing pin, breech face, and extractor, affect the quality of the mark and its reproducibility. Finally, the use of new technologies, such as three-dimensional surface topography, quantitative comparison features. Automated identification of cartridge-case toolmarks using databases, has significantly contributed to the improvement of the scientific objectivity of firearm examinations. However, a number of articles underline the need for further studies on the standardization of imaging procedures, the collection of comparative data, and statistical evaluation of comparison scores. This

issue is complicated by the variability of conditions in different databases, the lack of standardization of the comparison process. The possible differences in the results of automated and manual comparisons. The articles reviewed do not provide enough information to draw conclusions about thresholds of within-firearm variability of toolmarks or to evaluate how much individual characteristics are changed under different conditions. The next step in this research would be to perform long-term longitudinal studies of firearms from different manufacturers that include a significant number of shots and account for ammunition variability, as well as to validate the results of different comparison methods. In conclusion, the findings presented in the reviewed articles confirm the value of cartridge-case toolmarks as a source of evidence in firearms examinations while emphasizing the need for a more complex analysis that considers the effects of time and ammunition on toolmark variability.

## References

1. Kirk, Justin N., Eric F. Law, and Keith B. Morris. "Estimation of changes in breech face and firing pin marks over consecutive discharges and its impact on an IBIS® Heritage™ System." *Forensic science international* 278 (2017), [10.1016/j.forsciint.2017.06.021](https://doi.org/10.1016/j.forsciint.2017.06.021)
2. Law, Eric F., Keith B. Morris, and Casey M. Jelsema. "Determining the number of test fires needed to represent the variability present within firearms of various calibers." *Forensic science international* 290 (2018), [10.1016/j.forsciint.2018.06.010](https://doi.org/10.1016/j.forsciint.2018.06.010)
3. Ott, Daniel, et al. "Identifying persistent and characteristic features in firearm tool marks on cartridge cases." *Surface topography: metrology and properties* (2017), [10.1088/2051-672X/aa864a](https://doi.org/10.1088/2051-672X/aa864a)
4. Zhang, Kaifeng, and Yaping Luo. "Slight variations of breech face marks and firing pin impressions over 3070 consecutive firings evaluated by Evofinder®." *Forensic science international* 283 (2018), [10.1016/j.forsciint.2017.11.035](https://doi.org/10.1016/j.forsciint.2017.11.035)
5. Trejos, Tatiana, Sandra Koch, and Andria Mehlretter. "Scientific foundations and current state of trace evidence—A review." *Forensic Chemistry* 18 (2020), [10.1016/j.forc.2020.100223](https://doi.org/10.1016/j.forc.2020.100223)
6. Zheng, Xiaoyu, et al. "NIST ballistics toolmark research database." *Journal of Research of the National Institute of*

- Standards and Technology* 125 (2020), [10.6028/jres.125.004](https://doi.org/10.6028/jres.125.004)
7. Liu, Lijie, et al. "Measurement Studies Utilizing Similarity Evaluation between 3D Surface Topography Measurements." *Mathematics* 12.5 (2024), <https://doi.org/10.3390/math12050669>
8. Kumar, Sachil, Geetika Saxena, and Archana Gautam. "Forensic analysis and interpretation of tool marks." (2021), [10.5772/intechopen.98251](https://doi.org/10.5772/intechopen.98251)
9. Riva, Fabiano, et al. "Comparison and interpretation of impressed marks left by a firearm on cartridge cases—towards an operational implementation of a likelihood ratio based technique." *Forensic science international* 313 (2020), [10.1016/j.forsciint.2020.110363](https://doi.org/10.1016/j.forsciint.2020.110363)
10. Basu, Nabanita, Rachel S. Bolton-King, and Geoffrey Stewart Morrison. "Forensic comparison of fired cartridge cases: feature-extraction methods for feature-based calculation of likelihood ratios." *Forensic science international: synergy* 5 (2022), [10.1016/j.fsisyn.2022.100272](https://doi.org/10.1016/j.fsisyn.2022.100272)
11. Guyll, Max, et al. "Validity of forensic cartridge-case comparisons." *Proceedings of the National Academy of Sciences* 120.20 (2023), <https://doi.org/10.1073/pnas.2210428120>
12. Dong, Feng, et al. "Specificity of characteristic marks on cartridge cases from 3070 consecutive firings of a Chinese Norinco QSZ-92 9 mm Pistol." *Journal of Forensic Science and Medicine* 5.2 (2019), [10.4103/jfsm.jfsm\\_6\\_19](https://doi.org/10.4103/jfsm.jfsm_6_19)
13. Zhang, Hao, et al. "Correlation of firing pin impressions based on congruent matching cross-sections (CMX) method." *Forensic science international* 263 (2016), [10.1016/j.forsciint.2016.04.015](https://doi.org/10.1016/j.forsciint.2016.04.015)
14. Zhang, Kaifeng, Yaping Luo, and Peng Zhou. "Reproducibility of characteristic marks on fired cartridge cases from five Chinese Norinco QSZ-92 9× 19 mm pistols." *Forensic science international* 278 (2017), [10.1016/j.forsciint.2017.06.032](https://doi.org/10.1016/j.forsciint.2017.06.032)
15. Williams, Mike, Katie Addinall, and Liam Blunt. "The 2 stages of cartridge primer toolmark production and the implied impact of cartridge manufacturing tolerances." *Forensic Science International* 364 (2024), [10.1016/j.forsciint.2024.112231](https://doi.org/10.1016/j.forsciint.2024.112231)
16. Gerules, George, Sanjiv K. Bhatia, and Daniel E. Jackson. "A survey of image processing techniques and statistics for ballistic specimens in forensic science." *Science & Justice* 53.2 (2013), [10.1016/j.scijus.2012.07.002](https://doi.org/10.1016/j.scijus.2012.07.002)
17. Ghani, Nor Azura Md, Choong-Yeun Liong, and Abdul Aziz Jemain. "Analysis of geometric moments as features for firearm identification." *Forensic Science International* 198.1-3 (2010), [10.1016/j.forsciint.2010.02.011](https://doi.org/10.1016/j.forsciint.2010.02.011)
18. Suresh, R. "A simple method to compare firing pin marks using stereomicroscope and Microsoft office (Windows 8) tools." *Forensic science international* 277 (2017), [10.1016/j.forsciint.2017.05.024](https://doi.org/10.1016/j.forsciint.2017.05.024)
19. Geradts, Zeno J., et al. "Image matching algorithms for breech face marks and firing pins in a database of spent cartridge cases of firearms." *Forensic science international* 119.1 (2001), [10.1016/S0379-0738\(00\)00420-5](https://doi.org/10.1016/S0379-0738(00)00420-5)
20. Franklin, Veronica L., and Keith B. Morris. "A preliminary study of the manufacturing of breech faces." *Journal of Forensic Sciences* 69.6 (2024), <https://doi.org/10.1111/1556-4029.15626>
21. Monson, Keith L., Erich D. Smith, and Eugene M. Peters. "Repeatability and reproducibility of comparison decisions by firearms examiners." *Journal of forensic sciences* 68.5 (2023), <https://doi.org/10.1111/1556-4029.15318>
22. Le Bouthillier, Marie-Eve, et al. "Automated detection of regions of interest in cartridge case images using deep learning." *Journal of Forensic Sciences* 68.6 (2023), <https://doi.org/10.1111/1556-4029.15319>
23. Addinall, Katie, et al. "The effect of primer cap material on ballistic toolmark evidence." *Forensic Science International* 298 (2019), [10.1016/j.forsciint.2019.02.054](https://doi.org/10.1016/j.forsciint.2019.02.054)

24. Meral, Edanur, and Ahmet Oğuz Akyüz. "Firearm brand classification using deep learning on cartridge case images." *Forensic Science International* (2025), [10.1016/j.forsciint.2025.112671](https://doi.org/10.1016/j.forsciint.2025.112671)
25. Mookiah, Muthu Rama Krishnan, et al. "Automated segmentation of the breech and firing pin faces of fired cartridge case images." *Forensic Science International* 375 (2025), [10.1016/j.forsciint.2025.112554](https://doi.org/10.1016/j.forsciint.2025.112554)
26. Baiker-Sørensen, Martin, et al. "Automated interpretation of comparison scores for firearm toolmarks on cartridge case primers." *Forensic science international* 353 (2023), [10.1016/j.forsciint.2023.111858](https://doi.org/10.1016/j.forsciint.2023.111858)
27. Yiran, Xin, et al. "A review of firearm toolmarks identification: Progress, challenges, and perspectives." *Forensic Science International* (2025), [10.1016/j.forsciint.2025.112735](https://doi.org/10.1016/j.forsciint.2025.112735)
28. Alsdurf, Joseph W., Eric F. Law, and Stephanie C. Luehr. "Performance evaluation of a Cadre Forensics TopMatch-GS 3D system for cartridge case comparisons." *Journal of Forensic Sciences* 70.2 (2025), <https://doi.org/10.1111/1556-4029.15688>
29. Williams, Mike, Katie Addinall, and Liam Blunt. "The 2 stages of cartridge primer toolmark production and the implied impact of cartridge manufacturing tolerances." *Forensic Science International* 364 (2024), [10.1016/j.forsciint.2024.112231](https://doi.org/10.1016/j.forsciint.2024.112231)
30. Baldwin, David P., et al. "A study of examiner accuracy in cartridge case comparisons. Part 1: Examiner error rates." *Forensic Science International* 349 (2023), [10.1016/j.forsciint.2023.111733](https://doi.org/10.1016/j.forsciint.2023.111733)
31. Baldwin, David P., et al. "A study of examiner accuracy in cartridge case comparisons. Part 2: Examiner use of the AFTE range of conclusions." *Forensic Science International* 349 (2023), [10.1016/j.forsciint.2023.111739](https://doi.org/10.1016/j.forsciint.2023.111739)
32. M Baiker-Sørensen, Automated interpretation of comparison scores for firearm toolmarks on cartridge case primers, *Forensic science international*, (2023), [10.1016/j.forsciint.2023.111858](https://doi.org/10.1016/j.forsciint.2023.111858)
33. Baiker-Sørensen, Martin, et al. "Automated interpretation of comparison scores for firearm toolmarks on cartridge case primers." *Forensic science international* 353 (2023), [10.1016/j.forsciint.2023.111858](https://doi.org/10.1016/j.forsciint.2023.111858)
34. Williams, Mike, Katie Addinall, and Liam Blunt. "The 2 stages of cartridge primer toolmark production and the implied impact of cartridge manufacturing tolerances." *Forensic Science International* 364 (2024), [10.1016/j.forsciint.2024.112231](https://doi.org/10.1016/j.forsciint.2024.112231)
35. Algül, Asude Nur, and Aylin Yalcin Saribey. "Comparison of firing pin impressions on 15,000 consecutively fired cartridge cases From 9 mm Parabellum caliber pistol." *Forensic Science International* (2026), [10.1016/j.forsciint.2026.112841](https://doi.org/10.1016/j.forsciint.2026.112841)
36. Gambino, Carol, et al. "Forensic surface metrology: tool mark evidence." *Scanning* 33.5 (2011), <https://doi.org/10.1002/sca.20251>
37. Weller, Todd J., et al. "Confocal microscopy analysis of breech face marks on fired cartridge cases from 10 consecutively manufactured pistol slides." *Journal of forensic sciences* 57.4 (2012), <https://doi.org/10.1111/j.1556-4029.2012.02072.x>
38. Manzalini, Valentina, et al. "Firing pin impressions: a valuable feature for determining the orientation of the weapon at the time of shooting." *Forensic science international* 316 (2020), [10.1016/j.forsciint.2020.110519](https://doi.org/10.1016/j.forsciint.2020.110519)
39. Mattijssen, Erwin JAT, et al. "Interpol review of forensic firearm examination 2019–2022." *Forensic science international: synergy* 6 (2023), [10.1016/j.fsisyn.2022.100305](https://doi.org/10.1016/j.fsisyn.2022.100305)
40. Wen Z, Curran JM, Harbison S, Wevers GE. *Classification of firing pin impressions using HOG-SVM. J Forensic Sci.* 2023; 68: 1946–1957. <https://doi.org/10.1111/1556-4029.15377>

41. Meral, Edanur, and Ahmet Oğuz Akyüz. "Firearm brand classification using deep learning on cartridge case images." *Forensic Science International* (2025), [10.1016/j.forsciint.2025.112671](https://doi.org/10.1016/j.forsciint.2025.112671)
42. Chen, Kejin, et al. "A measurement anomaly detection method on metal cartridge cases based on PointNet++." *Digital Signal Processing* 161 (2025), [10.1016/j.dsp.2025.105120](https://doi.org/10.1016/j.dsp.2025.105120)
43. Vorburger, Theodore V., J. Song, and N. Petraco. "Topography measurements and applications in ballistics and tool mark identifications." *Surface topography: metrology and properties* 4.1 (2016), [10.1088/2051-672X/4/1/013002](https://doi.org/10.1088/2051-672X/4/1/013002)