The Effects of Lacquered Ammunition on the Toolmark Transfer Process

BY

NICOLE GROSHON
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THESIS

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Defense Committee:

Karl Larsen, PhD Chair and Advisor, Biopharmaceutical Sciences
Ashley Hall, PhD Biopharmaceutical Sciences
Donald Waller, PhD Biopharmaceutical Sciences
Ryan Lilien, MD/PhD Cadre Research Labs

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SUMMARY

When a firearm is discharged, the bullet and cartridge case acquire unique microscopic markings called ‘toolmarks’. Firearm forensics involves comparing two objects with similar toolmarks. These comparisons typically involve the bullets or cartridge cases found at a crime scene to ammunition that was test-fired with the suspected weapon. Historically, the primer faces of fired cartridge cases have been examined using a comparison light microscope and entered into a database. In recent years, agencies and laboratories have been transitioning to two and three-dimensional imaging to aid in faster comparisons with the help of automated search software programs. The database assigns a match score for the cases and the examiner makes a final comparison of the evidence and test fired ammunition to determine if there is a true match.

One troublesome feature firearms examiners may encounter is the lacquer that is commonly used to seal the primer of cartridges. The purpose of the sealant is to prevent moisture from making contact with the gunpowder inside the cartridge, which would render it useless. So far, little research has been done to test the effects of lacquer on the transfer toolmark process on fired ammunition. Whether an examiner prefers using the comparison light microscope or virtual imaging, the lacquer may need to be removed at some point during the examination as it tends to chip and flake off in patches thus completely changing the topography of the surfaces compared. There has been concern, however, that the cleaning process may destroy some of the individual characteristics that are also necessary for comparison. In this study we aim to examine several different firearms to determine if lacquer affects the toolmark transfer process.

I. INTRODUCTION

A. Firearm Forensics

i. History

The use of firearms and toolmark examination in criminal investigations dates back nearly two centuries ago to the first documented case in the City of London, England in 1835 [1]. A homeowner was fatally shot and the servant quickly became the main suspect. A local police officer named Henry Goddard examined the evidence and was successfully able to identify the mold mark made by the projectile's manufacturer [2]. Goddard also determined that the paper patch which was used as a seal between the projectile ball and the gunpowder had been torn from a newspaper found in the servant's room. Goddard's keen observations and detailed examination of the physical evidence were instrumental in bringing justice to the guilty party [1].

For the next several decades, firearms examination consisted of simple identification of general characteristic features such as caliber, macroscopic imperfections of the bullet, or the shape and type of bullets that were utilized [2, 3, 4]. One of the first cases in which firearms identification was used in the United States involved investigating the death of Confederate General Stonewall Jackson during the Civil War in 1863 [1]. The fatal bullet that struck him on the battlefield was collected, and the shape and caliber were examined. The Union Army was known to use a 58 caliber minié ball projectile during battle, and Stonewall Jackson was hit by a 67 caliber ball, which could have only been fired by one of his own men [1, 2]. In 1864, Union General John Sedgwick was also fatally shot during the Civil War. An examination of the caliber and hexagonal shape of the bullet revealed it was consistent with the ammunition of a Whitworth rifle, known to have been imported from England by the Confederates for sniping purposes. It was later estimated that General John Sedgwick was shot from nearly 800 yards away [1].

In 1907 in Brownsville, Texas, several soldiers from a nearby U.S. Army Infantry Regiment were allegedly involved in a riot which involved the firing of nearly 200 rounds of ammunition [1, 2]. Following the riot, 39 fired 30-caliber cartridge cases and several fired bullets were recovered from an alley in the vicinity. Later they were sent to Frankfort Arsenal for examination where they were compared to the rifles that were suspected of being used during the riot. The arsenal staff successfully devised a method and identified 33 of the fired cartridge cases as having been fired from four of the submitted rifles. No conclusions were made on the remaining six cartridges or any of the recovered bullets [1]. This report, titled the "*Study of the Fired Bullets and Shells in Brownsville, Texas, Riot,*" marks the first serious study that attempted to individualize fired cartridge cases to specific rifles, and represented one of the first recorded examinations of fired cartridge cases in history [1, 2, 5].

In 1912, Professor Victor Balthazard gave a lecture to the Congress of Legal Medicine on a firearms case he recently studied [1, 6, 7]. For this specific case, Balthazard used enlarged photos to illustrate the 85 points of comparison between a fatal bullet and a test fired bullet. During his lecture, he explained how the same diagramming technique can be applied when comparing the firing pin impression, breech face, and ejector marks of fired cartridge cases [1]. This lecture and his published papers titled "Identification des Projectiles de Revolver en Plomb Nu" (Identification of Revolver Projectiles of Plain Lead) and "Profectionment a la Methoded Identification des Projectiles" (Perfecting the method on the identification of projectiles), have been recognized as instrumental in establishing "ballistics" as a legitimate section of forensic science [1, 3].

One notoriously mishandled 1915 firearms case involved New Yorker, Charles Stielow. Stielow's employer and the employer's housekeeper had been fatally shot and after observing abnormal scratches on the bullets from the scene, an alleged firearms examiner determined they must have been fired from Stielow's revolver [1, 3]. Despite the record stating there was mishandling of evidence and the crime scene had been trampled by curious on-lookers, Stielow was placed in prison and sentenced to death. Fortunately the Governor of New York was unsatisfied with the proceedings and ordered a reinvestigation of the evidence presented by special investigator Charles E. Waite, and microscopy expert Max Poser. Together they determined that Stielow's revolver could not have been used to commit the crime and Stielow was released from prison soon after [1, 3].

Firearms identification continued to gain traction as a science in the 1920s and 1930s. In 1921, a court in Oregon allowed a Sheriff to provide expert testimony involving the identification of a fired cartridge case to an evidence rifle, marking the first time firearms identification was admissible in the courtroom [1, 8]. Later in 1921, Paul V. Hadley was tried for the murder of a woman and attempted murder of her husband [1]. Upon arrest, Hadley was found to be in possession of a 32 caliber Mauser pistol and several cartridges. Attorney Arthur J. Eddy had previously conducted research in firearms identification and had experience comparing fired cartridge cases. With the help of a professional photographer, Eddy provided the jury with data from his extensive testing along with diagrams demonstrating how he had drawn the conclusion that Hadley's pistol was the weapon used in the crime. The defense argued that Eddy was not an expert in the field. However the judge overruled their request stating that Eddy was "merely showing the results of his exhaustive research and experimentation" and characterized Eddy's testimony as that of a "semi-expert" thus allowing him to testify [1]. Hadley was convicted largely due to Eddy's testimony and therefore the defense moved to appeal the case. After careful consideration, the Arizona Supreme Court upheld the lower court's decision, ~~marking~~ distinguishing the first case in which a Supreme Court recognized ballistics evidence as valid and admissible [1, 2].

In order to better assist law enforcement agencies throughout the United States, the "Bureau of Forensic Ballistics" was formed in 1925. The Bureau consisted of Charles E. Waite, Phillip O. Gravelle (a microscopist and photographer), John H. Fisher (a tool designer), and Calvin H. Goddard (a medical doctor who later became recognized as the "father of modern firearms identification") [1, 3, 13]. Together Waite, Gravelle, Fisher, and Goddard were responsible for introducing the comparison microscope to firearms examination, which included the use of special stages and bullet mounting devices developed by Remington Corporation [3]. The introduction of the comparison microscope changed the trajectory of the science as it allowed for a significant increase in the examiner's ability to identify consistent striae so much so that it still remains at the forefront of instrumentation being used in the field today (1).

On April 15, 1920, a clerk for a shoe company in South Braintree, Massachusetts, was shot and killed along with his guard. The murderers were described as two Italian men and escaped with more than $15,000 [1]. Having fit the police description, Nicola Sacco and Bartolomeo Vanzetti were arrested and charged with the crime while attempting to flee via car. Although they were carrying guns, and despite their attempt to falsify statements upon their arrest, on July 14, 1921 both men were convicted and given the death penalty. The following month, on August 23, Sacco and Vanzetti were executed electrically. Several years later in 1961, modern forensic techniques and test fires collected from Sacco's gun proved it was his gun that killed the guard. To this day there is little evidence to substantiate Vanzetti's guilt [3, 4, 5].

On February 14, 1929, seven gangsters were brutally gunned down in an abandoned warehouse in Chicago, Illinois. Soon to be known as the “St. Valentine’s Day Massacre”, rumors quickly spread that there was possible police involvement in the act. Grand jury foreman B.A. Massee hired Calvin Goddard of the Bureau of Forensic Ballistics to examine and test fire all the police weapons and compare them to the collected evidence. Goddard was able to conclusively state that the killers used a 12-gauage shotgun and two Thompson submachine guns (one with a 50-round drum magazine) to commit the crime, noting that none of the police-issued weapons could have been used. Shortly after, weapons that had been confiscated from a rival ganger’s home were identified by Goddard to be consistent with the evidence found at the scene. Following his successful investigation into the type of ammunition and firearms used in the St. Valentine’s Day massacre, Goddard was offered a position as the Director of the Scientific Crime Detection Laboratory (SCDL) which was affiliated with the Northwestern University Law School in Chicago, Illinois [1, 14, 15, 16].

In 1932 the Federal Bureau of Investigation (FBI) was formed by Director J. Edgar Hoover to help further assist laboratories in criminal investigations [1, 3]. As the FBI quickly grew from having one member on staff to being the largest crime laboratory in the United States, Calvin Goddard (SCDL) assisted with training many of their new employees [1]. By 1934 there were twelve jurisdictions of superior courts in the United States that had accepted the concepts supporting firearm identification [3, 14, 15]. Although the courts began to acknowledge firearms identification as a science, there was still much disagreement over which requirements were needed to declare a true identification. In 1935, United States Army ordinance officer Major Julian S. Hatcher published two works titled “Textbook of Firearms Investigation, Identification and Evidence" and "Textbook of Pistols and Revolvers." Both received high reviews and were quickly adopted for reference by many firearms examiners across the country [1].

In 1942, scientists David Q. Burd and Paul L. Kirk carried out several experiments in attempt to better determine what criteria should be necessary in order to reach a positive identification when comparing toolmarks [17, 18]. Their article explained that for every one hundred striations, the examiner should have at least sixty percent matching striae in order to reach a conclusion that they were fired from a common source. If only forty percent of the lines matched, it was an indication of a "no match", and anything between that forty and sixty percent was considered questionable [9, 19]. Burd and Kirk developed these ranges after finding that two new and seemingly similar screwdrivers gave a twenty to twenty-five percent match [9, 18, 19].

By 1958 the Director of the Oakland Police Department Criminalistics Section, John E. Davis, published his work titled "An Introduction to Tool Marks, Firearms and the Striagraph," claiming that toolmark comparisons should not be approached in a statistical fashion [1, 20]. He stated that there should be no rules, formulas or required number of points needed to reach the conclusion of an identification. Even more so, he felt that statistical studies were not amenable to striation comparisons and argued that the conclusion reached should be based largely on the experience and methods of the examiner. Davis is well known for constructing instruments such as the striagraph which was a measuring and recording device used in the analysis of micro-surface contours or toolmarks [1]. The invention of the striagraph is discussed in greater detail in a later section. At the time, Davis' methods were considered novel and even revolutionary [20].

In 1959, Alfred A. Biasotti published a statistical study quite contradictory to Davis' claims regarding firearms identification. His study involved two groups of guns (16 previously used and eight brand new) and consisted of nearly twelve hundred comparisons [21]. Using probability estimations, Biasotti concluded that the percent of total matching striations is unimportant once the idea of consecutive lines is taken into account. When only a relatively few matching lines are associated by consecutiveness, one can conclude a match with a high degree of certainty [21]. For the types of bullets he compared, this meant that the presence of only three or four consecutive matching lines would suffice before a match or identification is made. Even after years of work, Biasotti concluded that in order to formulate objective criteria in toolmark comparisons, much more statistical data must be produced and researched [22, 23, 24].

On April 4th, 1968, Dr. Martin Luther King, Jr. was assassinated while standing on the second floor of his motel balcony in Memphis, Tennessee [1]. Shortly following the crime, a high-power rifle was recovered. Partial latent fingerprints were developed by the FBI Latent Print Unit and after searching their print card file for several months, they discovered that the prints belonged to a man named James Earl Ray [1]. A firearms examination report concluded that the recovered cartridge cases originated from the suspect’s firearm, however, Robert A. Frazier, a senior member of the FBI Firearm’s Unit explained that it was not possible to determine if the bullets found at the scene had been fired from the recovered rifle [1]. Ray was arrested several months after the assassination and confessed to having shot Dr. King. He was later tried in court and sentenced to life in prison [1].

After several decades of research, numerous pioneers had published their theories and it became apparent there was a need for an association to organize the discipline’s requirements as well as help share new ideas in the growing field [25, 26, 27]. In 1969, thirty-five police officials and civilian specialists from the United States and Canada gathered at the Chicago Police Department Crime Laboratory and formed the Association of Firearm and Tool Mark Examiners (AFTE) [1, 28]. The first officers elected to lead the association were President

Walter J. Howe from Wilton, Connecticut, Secretary John C. Stauffer from the Chicago Police Crime Laboratory in Chicago, Illinois, and Charles M. Wilson from the Wisconsin State Crime Laboratory in Madison, Wisconsin [1]. In the 1980s both AFTE and the FBI released new universal training material for the field. The AFTE Training Committee published a 400-page manual that could be tailored to meet the needs of each agency as well as act as a modular training guide for new examiners [1]. Shortly after, the FBI's Forensic Science Research & Training center (FSRTC) in Quantico, Virginia, announced the creation of their training course titled "Specialized Techniques in Firearms Identification" which aimed to cover a variety of subjects designed to enhance the level of proficiency for firearms examiners [1].

In 1980, AFTE also released the first edition of an official glossary which provided definitions, illustrations, commonly used abbreviations, various formulas for determining bullet energy, and rate of spin, along with other useful chemical formulas for examiners in the field [1]. Since then several editions have been released, with their sixth and most recent edition published in 2013. The committee acknowledges that this type of reference work will never be finalized or regarded as complete [28]. Throughout its years, the AFTE committee has kept with a qualitative (non-numerical) standard for determining if a mark did originate from a specific tool and has remained steadfast even when the new Daubert requirements were introduced in the courtroom.

ii. Frye and Daubert Criteria

In 1923, a standard of admissibility of scientific testimony was set by the District of Columbia Court of Appeals in the case of *Frye v. United States* [29]. For nearly 70 years, scientific advancements were admissible in court only once they gained general acceptance in their field. In 1993, the United States Supreme Court overruled the nationally followed Frye

Standard when deciding *Daubert v. Merrell Dow Pharmaceuticals* [30]. In Daubert, the court dismissed the "general acceptability" standard and established that the Federal Rules of Evidence would control the issue of admissibility of expert testimony, with a major factor being Rule 702 which aids the judge in determining which attributes qualify an expert. Under Daubert, expert testimony must meet these four criteria in order to be admissible in court: 1) the scientific principle can be tested; 2) the potential error rate is known; 3) there must be peer reviewed publications; and 4) it must be generally accepted in its particular scientific community. Through these criteria, Daubert essentially placed the presiding judges into gatekeeper positions, leaving them to decide what is admissible and what is not. While Daubert is now the controlling standard for all federal cases, not all states have adopted it and many still use Frye or some modification of it, when determining admissibility [31, 32, 33, 34].

Firearm and toolmark examination meets the criteria set forth by Daubert, but many attorneys have sought to have the examiner's testimony omitted from cases, claiming the comparisons are not scientifically valid or that the examiner's conclusions are subjective and should be deemed inadmissible [14, 31, 35]. However, the field's literature has been tested and peer-reviewed, the findings are generally accepted, and periodic proficiency tests have been implemented [36, 37, 38]. In attempt to reinforce the original statistical approaches similar to that of Davis, numerous forensic specialists have tested comparative statistical algorithms to aide in objective toolmark comparisons in attempt to solidify its admissibility in the courtroom as discussed in a later section [14, 31].

iii. Manufacturing Process of Cartridges

A cartridge contains four parts: the cartridge case, primer, propellant, and a projectile (bullet) [2,10]. The cartridge case manufacturing process begins with drawing a cartridge cup from a brass blank or rod [2, 39]. The cup of brass is annealed, or heated in a furnace to relieve strains in the metal, and then washed in an acid bath to remove any surface impurities [2, 39]. A brass cup may be drawn and heat-treated several times, depending on the desired length of the finished case [2]. During the drawing process, a punch press is inserted into the center of the cup to maximize the diameter and length of each cartridge case. The case will be thinnest at the mouth to allow flexibility for holding the bullet, and thickest at the closed end to withstand firing pressures [2]. The base of the cartridge case is flattened and stamped with a bunter which creates the head stamp and primer pocket [2, 40]. The edges of the case head are smoothed and finished using a machining tool or lathe [2, 41]. A head turning machine is used to punch a flash hole into the primer pocket which allows fire from the primer to reach the propellant charge [2]. The primer cup and proprietary explosive primer pellet are inserted. A drop of nitrate sealant or lacquer is applied as a water-proofing agent [2, 28]. In the final manufacturing steps, the smokeless powder (propellant) is inserted in the open end of the cartridge case, followed by the bullet being crimped into place [42, 43]. Each cartridge case is thoroughly inspected prior to being cleared for use [2].

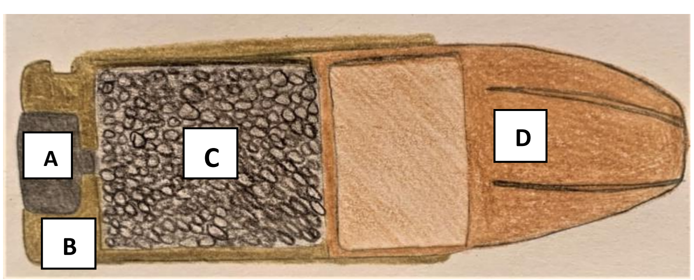

Figure 1: A) Cartridge Case, B) Primer, C) Propellant & D) Projectile/ Bullet

iv. Firearms and Tool Mark Examiner Training

The firearm and toolmark section of forensic science is specifically devoted to tools and the marks that they create [44]. During training, new examiners receive basic instruction on the different types of metals, metal deformation, chip formation, metal shaping processes, tools and tool actions, and toolmark identification [42]. A tool, as defined by the Association of Firearms and Tool Mark Examiners is, "An object used to gain mechanical advantage", and when two hard objects are brought into contact with each other, the softer one is marked as a result [28]. This knowledge also stems from Locard's Exchange Principle which states that when two objects come into contact, there will always be an exchange of material, such as a toolmark, fingerprint or other trace materials [9, 45].

Despite it being nearly impossible to list the tools produced by all manufacturers, significant studies involving the various toolmarks created by knives [46, 47], bolt cutters [48, 49], drill bits [50], rotary glass cutters [51] and cast bullets [52], all reach the same conclusion: each tool will leave its own unique marking. Throughout their training, examiners become familiar with the common tools seen in casework and are cognizant of the many factors that alter the appearance of a toolmark, such as the surface material or type of pressure, direction and angle that is used [42].

Firearms identification is a specialized area of toolmark identification concerned with identifying the firearm or parts of a firearm that generate the toolmarks observed on a fired ammunition component [42]. The identification of a cartridge case or bullet from a known firearm is determined based on the class, subclass, and individual characteristics found while microscopically comparing the evidence to test-fired ammunition. Class characteristics as defined by the Organization of Scientific Area Committees (OSAC) for forensic science are the "observable features of a specimen which indicate a restricted group source. They result from design decisions made by a manufacturer that are within acceptable manufacturing tolerances and are, therefore, determined prior to manufacture" [28, 38]. Some examples of class features that are predetermined by the manufacturer are caliber, type of cartridge, the size, and shape of the firing pin (be it spherical or elliptical). Subclass characteristics are features that may be produced during manufacture that are consistent among items made by the same tool. These features are not determined prior to manufacture and are more restrictive than class characteristics [28]. An example of a subclass characteristic would be a notch in the machinery that transfers a distinctive mark to all parts made by that manufacturer until that faulty piece of machinery is replaced. Individual characteristics are features that are unique to that specific firearm that result from use, corrosion, or damage, such as pitting found on a breech-face due to buildup of material on the firing pin [42, 53, 54, 55, 56]. A firearms examiner trainee will learn to categorize evidence based on class characteristics and will either eliminate or include it for further examination while comparing the unknown sample to test-fired ammunition.

The two main types of toolmarks created when a firearm is discharged are impressions and striations [28, 57]. When a firing pin strikes the primer on the base of the cartridge case, the expanding gases create a small explosion inside the chamber pushing the bullet forward out of the barrel and simultaneously the cartridge case back against the breechblock. In an auto loading or repeating firearm, an ejector tosses the case out to make room for the next cartridge [39, 42, 43]. Impressed marks are made by the firing pin and breechblock on the primer. The breechblock pattern impressed into the primer will vary depending on manufacturing technique, and the amount of recoil of the cartridge which can range from 10,000 – 50,000 lbs/ sq. inch depending on the type of firearm [3]. The general impression on a breech face can be categorized as parallel, concentric, arched, or granular in pattern [58]. Striations can be found on the sides of the bullet (lands and grooves) from traveling through the barrel, in a firing pin drag when the firing pin remains forward during the extraction of the cartridge case, or as an aperture shear when the primer is scraped by the firing pin hole during ejection [59]. An aperture shear and firing pin drag may not appear every time a cartridge is fired, but they are useful when orientating a cartridge case for comparison.

The impressions and striations on the evidence and on test fired ammunition are examined using a comparison microscope which is composed of two compound microscopes connected by a system of lenses, prisms, and mirrors that are known as an optical bridge [2, 53, 60, 61]; see Figure 1. The bridge allows an examiner to observe and compare two physically separated but optically joined objects simultaneously in a single field of view, split by an optical hairline [2]. After comparing several test fired specimens to one another to establish the major repeating features, an examiner will position the evidence (cartridge case or bullet) under one compound microscope objective, and the test-fired, known-evidence under the second compound microscope objective. Both specimens are brought into focus at the same magnification (typically 20x or 40x), lighting sources should be adjusted as necessary, and the toolmarks are lined up on the optical hairline to determine whether they correspond to one another accordingly [2]. All striations and impressions previously discussed may be used to make a comparison. In order to reduce the likelihood of missing features on the cartridge case or bullet, the two samples should be compared under the same lighting conditions and at the same angles [2, 9].

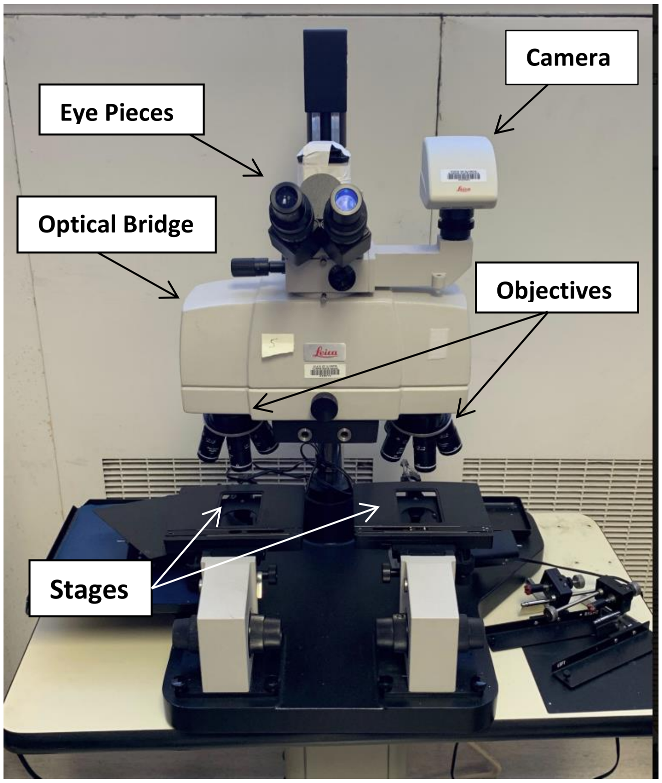

Figure 2: Leica Comparison Microscope

Once a firearm toolmark identification is made, four different statements are expected to be true: 1) the suspect firearm was used to make the markings found on the evidence, 2) the firearm has not been damaged or altered since firing the evidence ammunition, 3) the evidence has sufficient unique features for comparison, and 4) the firearm's working surface has an individual surface finish [62]. The three conclusions that can be drawn from comparing an evidence cartridge case (unknown source) to a test fired cartridge case (known source) are exclusion, inconclusive, or identification. The Association of Firearm and Tool Mark Examiners (AFTE) explains that a comparison must be classified as an exclusion when the unknown and known samples differ in class characteristics, such as caliber [28]. OSAC describes an exclusion as justified when the "observed characteristics of the items in question provide extremely strong support for the proposition that they were marked by different tools and extremely weak or no support for the proposition that the two were marked by the same tool." This conclusion is based on the demonstrable differences in class, subclass or individual characteristics, task-relevant information and the cumulative results of training and casework that have either been performed, peer reviewed, or published by a peer-reviewed journal [28, 38]. An inconclusive association is formed when all class characteristics are similar, but there are not enough individual characteristics present in order to claim that the cartridge cases were discharged from the same firearm. If a firearm does not seem to consistently produce an aperture shear and that is the only toolmark it produces, this may lead to an inconclusive result during comparison. An identification is made when the class and individual characteristics of the evidence and test fired items are in agreement with one another, with no known differences [54, 56].

As previously mentioned, AFTE accepts a non-quantitative position on the theory of identification of toolmarks. AFTE's theory simply states, the conclusion of 'identification' can be made when the unique surface contours of two toolmarks are in "sufficient agreement" [28]. To simplify, in order to conclude two marks have sufficient agreement, examiners must acknowledge that the possibility of another tool making these marks is so highly unlikely that it be considered practically impossible [28]. OSAC explains that an identification is the strongest statement of association expressed in forensic firearm and toolmark examination and examiners may not come to this conclusion often because it is difficult to prove "without doubt" without testing all the tools that exist in the world [28, 38]. In recent years, many scientists have attempted to solidify uniformity and objectivity in the field by creating new technologies that automate and supply a statistical foundation to the comparisons being made. However, until a system is tested and universally accepted, OSAC advises all firearms and tool mark examiners against the following while drawing conclusions and providing expert testimony: "1. An examiner shall not assert that two toolmarks originated from the same source to the exclusion of all other sources. This may wrongly imply that an Identification conclusion is based upon a statistically derived or verified measurement or an actual comparison to all other toolmarks in the world, rather than an examiner's expert opinion, 2. An examiner shall not assert that examinations conducted in the forensic firearms and toolmarks discipline are infallible or have a zero error rate. An examiner shall not provide a conclusion that includes a statistic or numerical degree of probability except when based on relevant and appropriate data" [28, 38].

v. Forensic Tools and Technology

In 1925, Colonel Calvin Goddard and his associate, Phillip O. Gravelle, developed the first comparison microscope which has become the universal tool used for firearms comparison ever since [2]. Although the comparison microscope has remained the most widely used instrument in the field due its relatively low cost and ease of operation, numerous scientists and engineers have attempted to improve upon it by adding camera systems or automated software that can identify individual features, as well as recall possible matches in a database collection.

In 1958 John E. Davis introduced the striagraph, a specialized instrument he described as, "primarily a measuring, tracing and recording device suited to the analysis of micro surface-contours, that is, to the detection of microscopic irregularities in surface smoothness" [1, 61]. Years later, in 1970, Californian toxicologist, J.W. Brackett, published a study in which he developed a theoretical basis for striation analysis. He simplified striations from a three dimensional comparisons to a two dimensional one, similar to what one does while using the comparison microscope. Brackett laid the foundation for future studies by describing the newly invented computer as a vital tool when applying his processes and principles [63].

In the early 1990's it became more apparent that firearms were being used multiple times in separate unsolved crimes which lead the initiative for a searchable database of unmatched cartridge cases and bullets. Shortly after, the FBI released DRUGFIRE, a multimedia database imaging system that automated the comparison of images of only cartridge cases. Once a comparison was made, the camera captured an image for later reference [61, 64]. Several years later, the Bureau of Alcohol, Tobacco, Firearms, and Explosives (ATF) developed the 2D Integrated Ballistic Identification System (IBIS) with Forensic Technology, Inc. from Quebec, Canada to process images of fired bullets [55, 64]. In both systems, a digital camera is attached to a low powered light microscope which allows images to be captured and compared to a database of previously collected images. Potential matches are given a score and are ranked in a list for an examiner to analyze and form a conclusion [65]. Any potential identifications must be verified using a comparison microscope [2, 66]. Over time DRUGFIRE and IBIS were upgraded to image both fired cartridge cases and fired bullets, however, these databases were two separate systems that did not communicate with one another [67]. Examiners needed access to both systems to ensure that all cartridge cases and bullets had been searched, which created problems for most agencies that were on a budget [55, 68]. In 1996, the National Institute of Standards (NIST) in Gaithersburg, Maryland, was requested to lead in the syncing of both systems.

In 1999, the FBI and ATF joined forces to support the National Integrated Ballistic Information Network (NIBIN) which incorporated technology from both DRUGFIRE and IBIS. The NIBIN database uses the technical base from IBIS [69, 70]. Responsibility is shared between organizations for the proper maintenance of the system. The FBI oversees the communications network, while the ATF is responsible for the system sites [9, 55]. Over the years, several countries have implemented their own databases such as CIBLE (France), FIREBALL (Australia), ARSENAL (Russia), TAIS (Russia), and BALISTIKA (Turkey) [71].

B. 3D Topography Systems

Recently there has been a growing interest in utilizing 3D imaging technologies when comparing fired cartridge cases or bullets. One instrument known as the Stylus produces surface profiles and topography images by scanning the surface with a fine stylus [72]. As the instrument scans the surface, its vertical motion over the peaks and valleys is converted by a transducer into an electrical signal that is digitized, stored, and analyzed. Stylus instruments can have a very high resolution and are known for being quite accurate; however, the fact that they require surface contact limits their utility because of the potential for scratching the material under inspection. Stylus instruments have been used in research, but are not typically used as much as some of its optical counterparts such as confocal microscopy, coherence scanning interferometry, focus variation, and the photometric stereo [73, 74].

Confocal microscopy relies on the use of pinholes for height discrimination [75]. Incident light is focused through a pinhole, refocused onto the surface and reflected, then refocused through another pinhole in front of the detector. A strong signal will only be detected when the surface point is at the correct height. This discrimination enables the tool to detect variations in surface height and topography when the surface is vertically scanned along the optical axis of the microscope [76]. The vertical noise resolution and lateral resolution improve with the numerical aperture of the microscope. With a 50X objective, having a numerical aperture of 0.5, the vertical resolution can be as little as a few nanometers and the lateral resolution is a micrometer or less [76-79].

Coherence scanning interferometry (CSI) relies on interference between a beam of light reflected from the questioned surface and a beam of light reflected from a reference surface [80, 81]. When the optical paths reflected from the reference surface and the questioned surface are equal, an interference pattern of bright and dark fringes is formed on the camera detector, but as either optical path is changed, the fringe contrast disappears. The vertical noise resolution is typically a few nanometers but can get as small as 0.1 nanometers and the lateral resolution is approximately a micrometer, similar to that of confocal microscopy [82, 83].

In focus variation instruments, the height sensing function derives from locating the surface at its sharpest, best focus position in the microscope [84]. The peaks and valleys of the surface are focused at different positions as the surface scans vertically, a technique similarly utilized in confocal and coherence scanning interferometry instrumentation. Because the method relies on contrast in images resulting from peaks and valleys of surface features, averaging of individual pixels is required to provide the height sensitivity, which involves a collective response from neighboring pixels [84]. It has been found that the lateral and vertical resolutions of the focus variation method are more limited than those for confocal or coherence scanning, but further research must be done to determine whether this technique may be sufficient regardless [85].

Photometric stereo involves the decoding of shadow patterns on surfaces cast by multiple light sources to produce a surface topography measurement. Depending on the number and directions of the light sources, this method can have different results [86, 87]. Six each evenly spaced light sources illuminate the surface and the shadow patterns are analyzed. This produces a surface topography image. The method may utilize an additional feature called Gelsight, which eliminates the reflection of metallic surfaces often found on ammunition [87]. The microscope above the gel observes the shadows of the gel surface and the gel surface reproduces the underlying topography. This GelSight technology will be discussed further in the next section. The photometric stereo method may be less expensive and more convenient to use than other methods, but its resolution may not be as high as confocal microscopy or coherence scanning interferometry, and should be further investigated. A number of instruments that measure surface topography are now available for use in crime labs, some of which include the IBIS TRAX HD3D from Ultra Electronics Forensic Technology Inc. [88, 89], the Evofinder from ScannBi Technology [90], ALIAS from Pyramidal Technologies [91], and the Topmatch-GS 3D system from Cadre Forensics which is the photometric stereo instrument used to complete this study [92, 93].

C. TopMatch-3D Virtual Comparison Microscopy

In 2013, Cadre Forensics developed a 3D imaging and comparison instrument for cartridge cases called the TopMatch-3D High Capacity scanning system [92, 93]. This three-dimensional system was designed to improve upon the currently used 2D systems and remove lighting artifacts [66]. It allows the examiner to measure surface topographies, compute a match score, and annotate geometrically similar areas of the case [92, 94]. The TopMatch-3D High Capacity scanning system was the instrument used to complete this study.

When beginning a new comparison, the case number, date and other provided information may be entered into the database. The scanning tray allows 15 cartridge cases to be loaded at once and specific information regarding each cartridge case, such as type of firearm and caliber must be entered prior to scanning. Once all data is entered, the scanning tray is removed and the head of each case is cleaned using a soft brush or craft putty to remove any stray particulate. Plastic jaws hold each cartridge case in place just under the extractor groove, with the head stamp facing upward. Upon initial set up or anytime a new GelSight gel sheet is used, the ball grid array standard is placed in the first holder to confirm the scanner is calibrated. Once the cartridge cases are cleaned and in place, the tray is reinserted under the light-plate of the scanner and the examiner may begin scanning [93]. The system collects images of each head stamp and displays them as they are collected to confirm each cartridge case is centered correctly.

The examiner is then prompted to mount the gel for the final scanning process. Cadre examiners utilize GelSight technology, which is a clear elastomer with a thin layer of paint on one side that conforms to the shape of any surface pressed into it. This layer of elastic paint creates uniform surface features and removes the influence of any surface reflectivity commonly seen in other imaging systems [66, 92, 93]. The gel is placed on the holder and affixed to the light plate. A silicone roller is used to clean the gel and remove any air trapped between the plate and the gel.

The examiner then prompts the software to collect cartridge scans. The scanner raises each cartridge into the gel and the system focuses and collects images from six different positions to increase contrast and remove shadows, to calculate a surface topography measurement using the photometric stereo method. This method analyzes the illumination patterns of the cartridge to reveal the underlying surface topography. The use of gel reduces the effect of varying surface reflectance of the cartridge case. The electronics are enclosed in a black box to protect imaging from stray light or debris [92, 93]. A linear xy-stage allows fine positioning control. The setup contains an 18-megapixel Canon digital camera with a 65mm macro lens set to an image resolution of 1.4µm/pixel [92].

Shortly after scan acquisition, the breech-face is masked and color-coded using an auto-masking algorithm and then saved to the database for later review. Once the examiner chooses a cartridge for comparison, the spent cartridge cases are ranked from most to least similar as a function of the number and quality of matched features. At this time, the database search tool will display any cartridge cases with similar features that were previously masked in the breech face region. In the near future, Cadre plans to implement similar match scoring for other features that can be masked, such as the aperture shear and firing pin impression. The search tool is invoked when a firearm has not been recovered and test fires are unavailable, or if it had been previously entered into the database for an unsolved case. Once the examiner chooses a cartridge for comparison, the cartridge cases are ranked from most to least similar as a function of the number and quality of matched features. As a final step, the user will then utilize the virtual comparison microscopy tool to form a final conclusion on all cases in the list provided. Examiners can rotate, slide, increase contrast, zoom and change the angle of lighting for ease of use. Files can be saved and exported for later viewing [92, 93].

The TopMatch-3D High Capacity scanning system has been tested, validated, and is used in casework. In 2013, Cadre Forensics completed several experiments to validate the scanning hardware, the cartridge case scan tray, image analysis and matching algorithms. The first two experiments demonstrated the system's current performance on real-world cartridge cases, including 329 well and poorly marked cartridge cases collected from the 47 firearms: 2x Colt, 5x Hi-Point, 7x Fabrique Nationale, 5x Smith & Wesson, 5x Radom, 16x Ruger (including 10 with consecutively manufactured breech-faces), 5x Norinco, 1x FEG, 1x Springfield Armory [94-96]. The dataset consisted of three test fires of PMC Brand (brass cartridge case, brass primer), two test fires of Remington Brand (brass cartridge case, nickel primer), and two test fires of RWS

Brand (brass cartridge case, nickel primer) from each firearm. In the first experiment, the software was prompted to run an all-vs-all comparison of the 141 PMC brand ammunition (19,881 comparisons), and all computations were completed in less than 4 hours. For 79% of the cartridge cases, the top scoring candidate match has a score above 50 and 100% of these matches are correct while the remaining 21% of cases did not mark well enough for a significant match to be identified [95]. In this situation, the algorithm considers the cartridge cases with a match score less than 50 to be inconclusive and does not claim a match. It was found that a known match involving two poorly marked cartridge cases may have had a low match score, but a known non-match pair never had a large score, meaning no false positives were found during the experiment.

In the second experiment, the Remington and RWS brand ammunition were added to the test group and an all-vs-all software comparisons (108,241) required approximately 7 hours of computing [92]. It was found that the Remington and RWS brand cartridges did not pick up the same quality of toolmarks as the PMC brand ammunition which may be partially attributed to a manufacturing defect found in on the RWS brand ammunition. As a result, only 233 of 329 (71%) of the cartridge cases were considered sufficiently marked, compared to the 91% of the PMC brand ammunition [92]. Similar to the first experiment, the 1974 known matches have significantly larger scores than the 105,938 known non-matches. Once again, no known non-match had a score above 50 and there were no false-positives [92].

The third experiment consisted of ten pairs of matched knowns and fifteen individual ‘questioned’ (or unknown) cases [92]. The examiner was tasked with matching each questioned case with one of the known pairs. All test fires were Federal Cartridge ammunition (brass cartridge cases, nickel primer). In contrast to our first two experiments, the cases in this study were all strongly marked. All questioned cases were correctly identified with their matching known pairs, and no false-positives were given.

The GelSight technology has also been tested for reproducibility and persistence. To determine if there are any noticeable degradative effects caused by repeated scanning, the same cartridge case was scanned 30 times using a single piece of gel. It was found that the number of detected features remained fairly consistent from scan to scan [92]. For the persistence study, tests were done to determine whether a cartridge case leaves a 'memory' or imprint in the gel. After collecting 30 scans of a single cartridge case*a*, the same gelwas used to scan two different cartridge cases, *b* and *c*, and the images were compared. It was found that it would be highly unlikely that persistence effects would cause a false positive during comparisons.

An additional study involved over 100 firearms and 431 cartridge cases from the following manufacturers: Armi Fratelli, Baikal, Beretta, Browning Arms, Bryco Arms, Colt, Hi-Point, Fabrique Nationale, FEG, Heckler & Koch, Intratec, Kahr Arms, Keltec, S&W, Radom, Ruger, Norinco, Sig Sauer, Springfield Armory, Star, Taurus, Uzi, and Walther. A total of 417 of these 431 cartridge cases had a known match in the test set and 14 cartridge cases did not have a known match in attempt to mimic a real-world scenario. Each cartridge case received a ranked list of candidate matches. For 69% of the cartridge cases, the top scoring candidate match has a score above 50 and 100% of these matches are correct [97]. The remaining 31% of cartridge cases do not mark well enough for a significant match to be identified by the algorithm and would be deemed inconclusive by the typical examiner [92].

In 2018, Cadre released the results to their latest study titled, "Development and Validation of a Virtual Examination Tool for Firearm Forensics" where the scanner was evaluated in three separate experiments [98]. Each test set consisted of a total of seven cartridge cases (three known test fires, four unknowns) and the participating firearms examiners were asked to make comparisons using Cadre's virtual microscopy comparison tool. The first trial was done voluntarily at the Association of Firearms and Tool Mark Examiner conference and 100% of the conclusions made by the 11 participants were correct [98]. The test groups for Cartridge Case Test Sets 1 (CCTS1) & 2 (CCTS2) involved 56 participants and the scans were preloaded on a laptop and then sent to trainees and examiners. In CCTS1, 100% of the examiners and trainees made all correct identifications. In CCTS2, all examiners made 100% correct identifications, but one trainee made two false identifications and another marked an identification as inconclusive [98]. It is not known how far the trainees were in their onboarding process, however, more information will be requested of participants in future studies to better understand why such an error may occur.

II. EXPERIMENT

A. Lacquered Ammunition

Many cartridge manufacturers seal their primer with a spot of lacquer or nitrate polymer to prevent any moisture from contaminating the propellant, rendering the ammunition useless. It can be found in a variety of colors: red, green, pink, blue, brown and even colorless depending on the proprietary formulation set by the manufacturer. Some companies try to keep the lacquer pooled neatly in the annulus, the gap where the primer cap and the headstamp of the cartridge make contact, while others cover the entire primer face, as commonly seen on Sellier & Bellot ammunition (Figure 3). The lacquer coating ranges from about 0.01 mm to 0.045 mm in thickness (99) and has been known to bubble and crack from the heat and impact of firing as seen in Figure 4. Firearm examiners understand that a slight variance in surface texture and layering may cause significant changes in the way toolmarks transfer, however, at this time very little has been done to test the effects of the lacquer on the firearm toolmark transfer process.

Figure 3: Sellier & Bellot lacquered headstamps

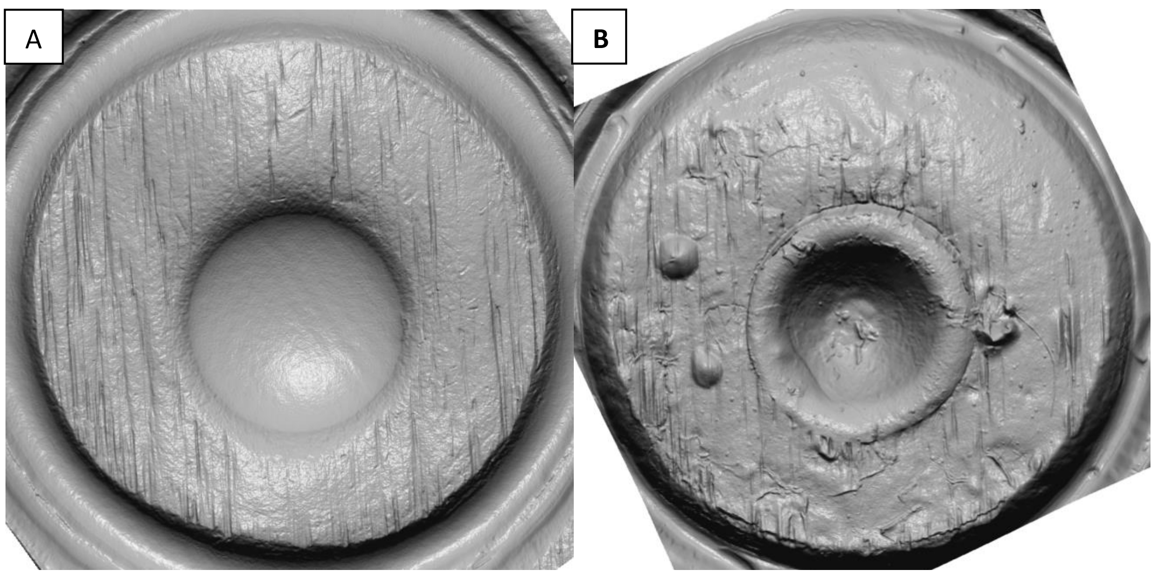

Figure 4: Cadre TopMatch-3D scanned image of a non-lacquered test-fired cartridge case (A) and a lacquered test-fired cartridge case (B); both were fired from the same 9mm Hi-Point.

In a 2013 study titled, 'Objective analysis of toolmarks in forensics', Taylor Grieve examined several types of fired ammunition to test how well serial numbers transfer from microstamped firing pins [100]. When a microstamped firearm is discharged, the serial number on the firing pin is impressed in the primer of the ammunition, allowing for easy comparison during investigations. Although the serial numbers did not always transfer well, it was found that comparisons could be successfully drawn, except when heavily lacquered ammunition, such as Sellier & Bellot, was used. On some cartridge cases, the lacquer seems to have softened the edges of the fine detailing needed to read the code properly [100]. In this particular study, the lacquer was not removed to see if legibility improved.

B. Hypothesis

The lacquer used to seal cartridges may interfere in the toolmark transfer process. The effects of lacquer should be better understood because if handled improperly, vital evidence will be lost.

C. Experiment Design

As an initial investigation into whether lacquer may have effect on the toolmark transfer process, a total of 125 non-lacquered and lacquered ammunition were test-fired and compared. Twenty-five 9mm firearms were selected from a reference collection at the Illinois State Police Forensic Science Center in Chicago, Illinois. Five different makes were chosen to provide a variety of breech-face and aperture shear patterns, and five of each make type were selected so similarities in the manufacturer's class characteristics could be observed as well. All firearms have an ID assigned by the laboratory, but for simplicity, they were each assigned a letter A through Y for this experiment (Table 1). Please note that Skyy & Sccy are the same manufacturer, as is with the Bryco, Jennings & Jimenez Arms makes that were used in this study.

Each firearm was test-fired five times using Sellier & Bellot ammunition. The first two cartridges were fired after cleaning with acetone to remove the lacquer (1_Control & 2_Control). Three cartridges were fired with the lacquer left intact (3_Lacquered, 4_Lacquered & 5_Lacquered) as seen in Figure 5. After all five cartridge cases were scanned using Cadre's TopMatch-3D scanner, the three lacquered cases were cleaned with acetone and rescanned (3_Cleaned, 4_Cleaned & 5_Cleaned). Each firearm corresponded to eight scans, for a total of 200. To keep these scans organized, the assigned firearm letter was placed in front of the cartridge file name. For example, for Firearm A (Table 1) the eight scans were labeled A1_Control, A2_Control, A3_Lacquered, A3_Cleaned, A4_Lacquered, A4_Cleaned, A5_Lacquered and A5_Cleaned.

Table 1: Firearm make, model, laboratory ID and assigned ID letter

ID Letter	Make	Model	ISP ID
A	Hi-Point	C9	GF120097
B	Hi-Point	C9	GF120099
C	Ruger	P85	GF130184
D	Ruger	P85 MKII	GF120085
E	Glock	26	GF130184
F	Glock	17	WF960141
G	Skyy	CPX1	GF130035
H	Skyy	CPX1	GF130033
I	Bryco	Jennings 9	GF120121
J	Bryco	Jennings 9	GF130110
K	Hi-Point	C9	CF020365
L	Hi-Point	C9	CF010046
M	Hi-Point	C9	GF120094
N	Ruger	P85	MF950161
O	Ruger	P89	CF030044
P	Ruger	P95DC	CF010035
Q	Glock	17	CF020179
R	Glock	19	CF010031
S	Glock	19	CF060006
T	Skyy	CPX1	CF130014
U	Sccy	CPX1	CF130019
V	Skyy	CPX1	CF130004
W	Jimenez Arms	JA Nine	CF080019
X	Jennings 59	Bryco	GF1250122
Y	Bryco	Jennings Nine	CF030132

Figure 5: Sellier & Bellot ammunition. Rows A & B were the acetone-cleaned Control Group and rows C, D & E were the Lacquered Group.

When visually comparing the test-fired cartridges, it became apparent that the quality of toolmarks significantly decreased from Control group, to Lacquered group (Figure 6) and then even more so once the lacquer was removed in the Cleaned group (Figure 7**)**.

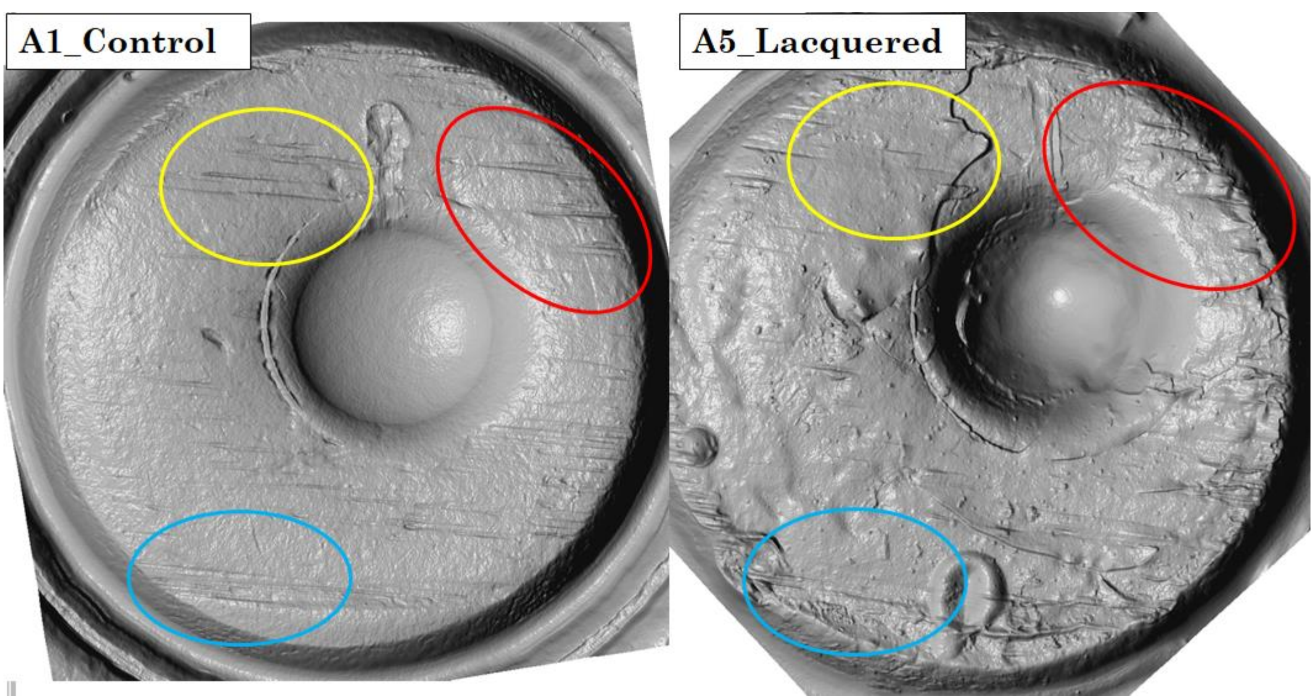

Figure 6: Firearm A (Hi-Point). A1_Control compared to A5_Lacquered; annotated with colored circles to highlight regions where toolmarks varied the greatest.

When comparing the yellow circles in Figure 6, the breech-face impression did not seem to transfer into the heavy lacquer (A5_Lacquered) as well as it did on the cleaned primer on the right (A1_Control). In the red region on the lacquered scan, the striations appear shorter and uneven, making comparison difficult. In the left blue circle (A5_Cleaned), some bubbling occurred and the build-up of lacquer where several fine striations should have appeared made this region difficult to view properly. In Figure 7, the lacquered scan from Figure 6 remains on the right side, but the left image is now the corresponding cleaned cartridge case scan (A5_Cleaned).

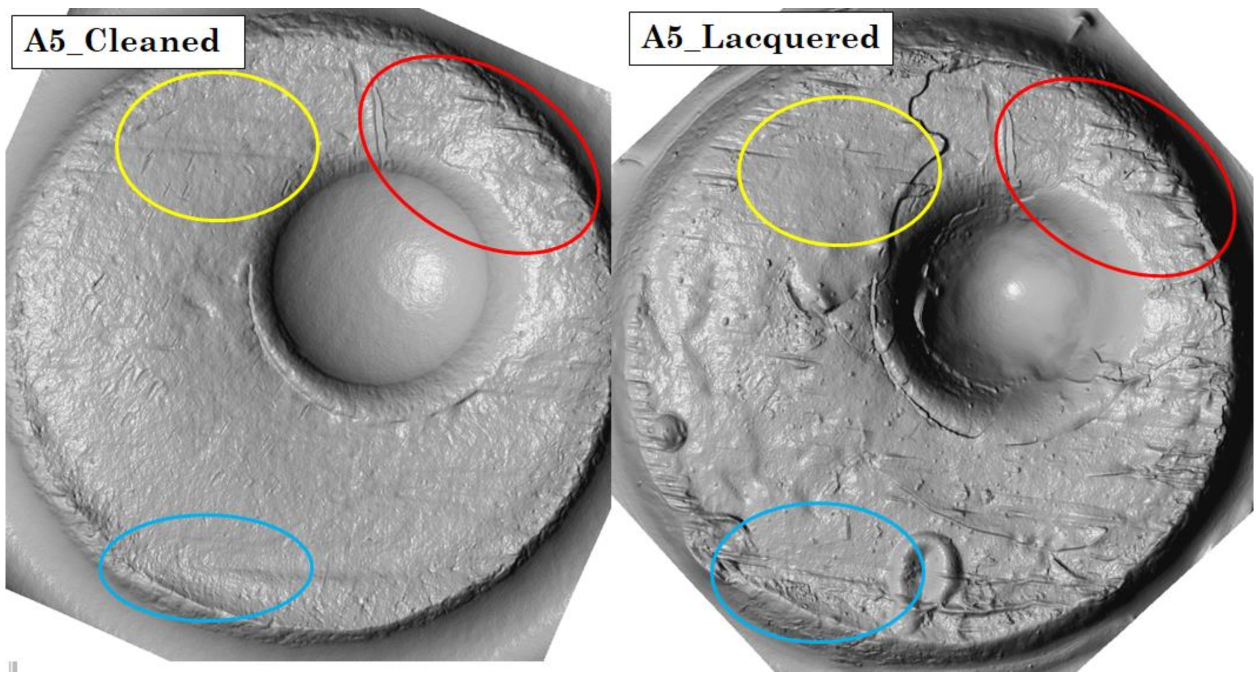

Figure 7: Firearm A (Hi-Point). A5_Cleaned compared to the same cartridge case when lacquer was left intact, A5_Lacquered.

After cleaning and rescanning, it can be seen in the yellow region that the striations that did not to transfer to the lacquer (A5_Lacquered) still transferred through to the primer, as seen in the A5_Cleaned scan. Although the striations are not well-defined, they do appear more similar to that of the Control scan in Figure 6. In the red circle on the cleaned scan, the striations are short and not nearly as defined as the lacquered and control scans and once cleaning of the lacquer occurred, the region in the blue area seems to have lost lots of detail.

Figure 8 is demonstrates the potential for losing fine details in a concentric breech-face impression if lacquer is removed prior to analysis. Notice how smooth the Cleaned breech-faces were compared to the patterns found on the Lacquered and Control scans.

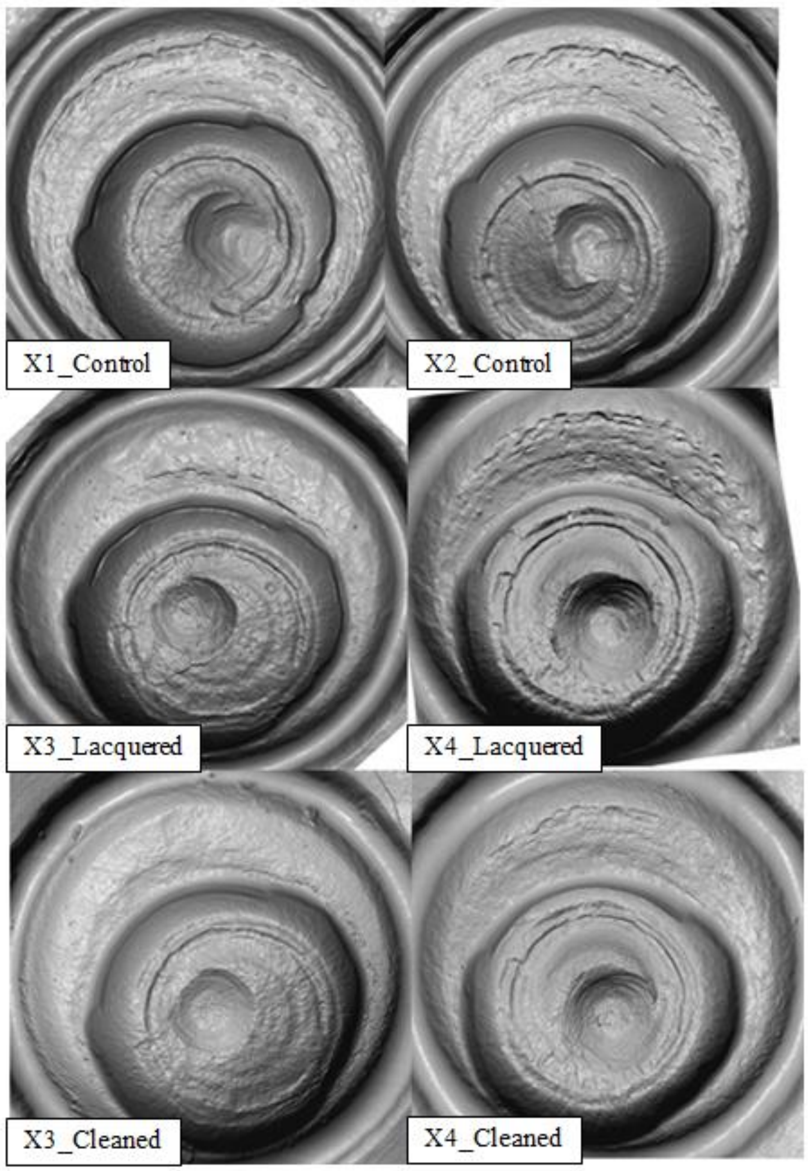

Figure 8: Firearm X (Bryco)

In order to quantify these differences, a new technique was implemented using the TopMatch-3D masking software. The two Controls from each firearm were displayed on the comparison screen and toolmarks that were observed in both test-fires were masked, or 'colored in'. All breech-face marks were masked in red and aperture shear marks were masked in green (Figure 9). Since these features are formed differently (impressed vs striated) they will be evaluated separately in this study.

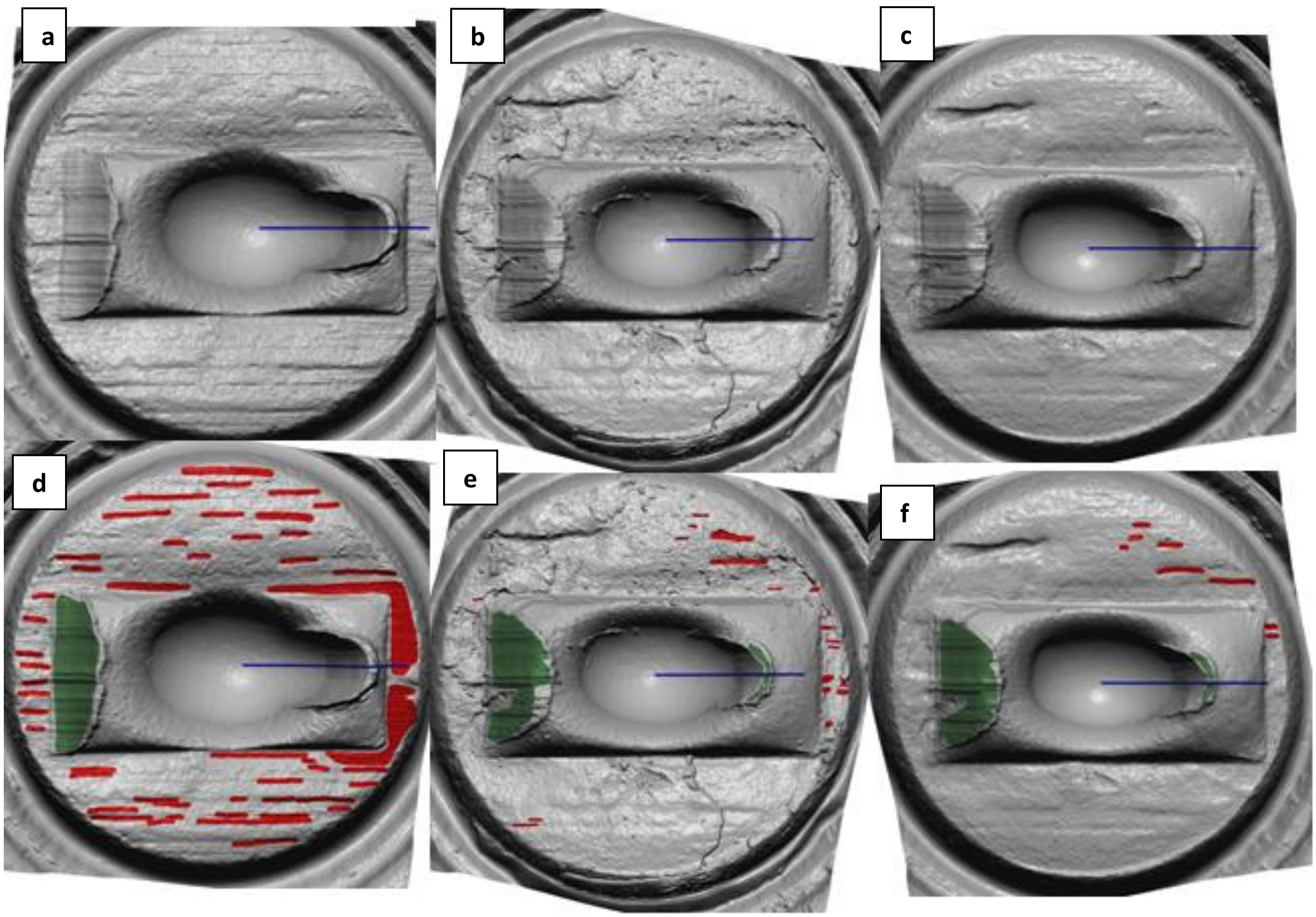

Figure 9: Firearm E (Glock). a) E2_Control, b) E4_Lacquered, c) E4_Cleaned, d) E2_Control (masked), e) E4_Lacquered (masked) and f) E4_Cleaned (masked).

Each Lacquered and Cleaned cases were compared with the Control cases and masked wherever similar features were observed. The pixels of each mask were counted using a Python script, and the pixels were then converted to total surface area by multiplying the number of pixels by the area of each pixel, 3.24 μm^2 . This value is determined by the lateral sampling resolution of the TopMatch system, 1.8 µm per pixel. The conversions for Firearm E (Glock) in Figure 9 are shown below in Table 2, but the complete chart of all calculations made can be found in the Appendix. A value of zero is found when there were no features to mask.

Table 2: Surface area values for Firearm E (Glock), Figure 9.

Name	BF μM^2	AS μM^2
E1_Control	1,040,461	597,851
E2_Control	1,432,232	475,139
E3_Lacquered	61,867	644,802
E3_Cleaned	0	571,335
E4_Lacquered	108,847	445,568
E4_Cleaned	83,355	477,132
E5_Lacquered	21,814	761,992
E5_Cleaned	11,745	658,478

D. Breech Face Results

The breech face and aperture shear values were separated into two tables and each surface area was converted to a percentage in relation to the Control 1 in its respective test group in order to normalize the data set. For example, breech-face B1_Control, surface area of 406,3307 μm^2, was set to 100% and B2_Control, surface area = 333,4572 μm^2, had 82% of the masked features compared to B1_Control. In Table 3, any breech face values for Control 2 that were greater than 110% of Control 1 were coded in blue. Any Control 2 values that were ±10% of Control 1 were left white, and any values less than 90% of Control 1 were coded green. Firearm F (Glock) and Firearm P (Ruger) did not have any suitable breech-face features to mask on their test-fires and because these impressions marked so poorly, the data for these two firearms was not included in the calculations.

As seen in Table 3, approximately 23% of the Control 2 breech-face values were greater than 110% of its corresponding Control 1 (blue), 44% of Control 2 values were within ±10%of their corresponding Control 1 values (white), and 31% were less than 90% of Control 1 (green). Ideally, every test-fire would match one another perfectly, but in the field of firearm forensics, slight variability is expected. Although there seemed to be quite a range in values, the average for Control 2 compared to Control 1 was approximately 104.7%, meaning less than 5% more features were masked in the Control 2 group.

Table 3: Comparing Control 2 breech-face percentages to Control 1

Firearm		Control 1 BF	Control 2 BF
Hi-Point	A	100	119
Hi-Point	B	100	82
Ruger	C	100	106
Ruger	D	100	79
Glock	E	100	138
Glock	F	N/A	N/A
Skyy	G	100	77
Skyy	H	100	90
Jennings	I	100	80
Jennings	J	100	215
Hi-Point	K	100	37
Hi-Point	L	100	138
Hi-Point	M	100	166
Ruger	N	100	92
Ruger	O	100	98
Ruger	P	N/A	N/A
Glock	Q	100	107
Glock	R	100	105
Glock	S	100	96
Skyy	T	100	59
Sccy	U	100	146
Skyy	V	100	99
Jimenez Arms	W	100	105
Bryco	X	100	69
Jennings	Y	100	105

White: Control 2 values ±10% of Control 1 (44%)
Blue: Control 2 values >110% of Control 1 (23%)
Green: Control 2 values <90% of Control 1 (31%)

When comparing a lacquered cartridge case scan to its corresponding cleaned cartridge case, similar calculations were applied, as shown in Table 4. If the features masked on the cleaned cartridge case were greater than 110% compared to its corresponding lacquered cartridge case, the value is coded blue. If the paired values are within ±10% of one another, they are left colorless and if they were less than 90% of the lacquered value, they are colored green. Approximately 6% of cleaned cartridge cases showed a greater than 110% increase in features than the corresponding lacquered cartridge case (blue), 54% of values were within ±10% of one another and 40% of the cleaned cartridge cases showed a decrease in masked features by more than 90% (green).

Table 4: Comparing Breech Face Impression Toolmarks: Clean Compared to Lacquered

Firearm		Control 1 BF	Control 2 BF	Lacq 3 BF	Cleaned 3 BF	Lacq 4 BF	Cleaned 4 BF	Lacq 5 BF	Cleaned 5 BF
Hi-Point	A	100	119	48	77	41	25	64	18
Hi-Point	B	100	82	54	42	13	9	59	13
Ruger	C	100	106	23	0	0	0	0	0
Ruger	D	100	79	0	48	12	12	0	47
Glock	E	100	138	6	0	10	8	2	1
Glock	F	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Skyy	G	100	77	11	0	11	8	34	16
Skyy	H	100	90	0	0	0	0	0	0
Jennings	I	100	80	87	78	58	82	83	82
Jennings	J	100	215	98	98	85	63	0	0
Hi-Point	K	100	37	26	4	16	15	12	17
Hi-Point	L	100	138	43	19	36	32	25	15
Hi-Point	M	100	166	52	17	53	21	59	36
Ruger	N	100	92	118	42	68	0	0	0
Ruger	O	100	98	104	27	114	89	61	29
Ruger	P	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Glock	Q	100	107	38	0	31	39	24	18
Glock	R	100	105	104	0	29	0	34	8
Glock	S	100	96	0	0	8	0	0	0
Skyy	T	100	59	0	0	0	0	0	0
Sccy	U	100	146	114	114	124	96	92	83
Skyy	V	100	99	20	12	28	10	24	10
Jimenez Arms	W	100	105	64	46	13	16	21	23
Bryco	X	100	69	28	24	64	38	55	49
Jennings	Y	100	105	0	0	27	30	31	30

White: Cleaned values ±10% of Lacquered (54%)
Blue: Cleaned values >110% of Lacquered (6%)
Green: Cleaned values <90% of Lacquered (40%)

E. Aperture Shear Results

The same two comparisons, Control 1 to Control 2 and the Lacquered cases to their corresponding Cleaned cases were then completed for the aperture shear. Ten firearms, all the Hi-Point and Bryco/Jennings/Jimenez Arms did not produce aperture shear marks on any of their test-fires, which excluded them from the following calculations. Approximately 20% of the Control 2 aperture shear values were greater than 110% of its corresponding Control 1 (blue), 40% of the pairs were within ±10% of each other (white), and 40% of Control 2 had 90% or less masked features when compared to Control 1 (green) as seen in Table 5. Again, the range may seem wide, but on average the Control 2 aperture shears were within96% of the Control 1 group.

Table 5: Comparing Aperture Shear Toolmarks: Control 2 compared to Control 1

Firearm		Control 1 AS	Control 2 AS
Hi-Point	A	N/A	N/A
Hi-Point	B	N/A	N/A
Ruger	C	100	95
Ruger	D	100	90
Glock	E	100	69
Glock	F	100	109
Skyy	G	100	75
Skyy	H	100	68
Jennings	I	N/A	N/A
Jennings	J	N/A	N/A
Hi-Point	K	N/A	N/A
Hi-Point	L	N/A	N/A
Hi-Point	M	N/A	N/A
Ruger	N	100	103
Ruger	O	100	111
Ruger	P	100	234
Glock	Q	100	70
Glock	R	100	46
Glock	S	100	122
Skyy	T	100	97
Sccy	U	100	105
Skyy	V	100	42
Jimenez Arms	W	N/A	N/A
Bryco	X	N/A	N/A
Jennings	Y	N/A	N/A

White: Control 2 values ±10% of Control 1 (40%)
Blue: Control 2 values >110% of Control 1 (20%)
Green: Control 2 values <90% of Control 1 (40%)

The aperture shears on the lacquered cartridge case scans were compared to those of the cleaned cartridge case scans in a similar fashion (Table 6). Approximately 22% of cleaned cases showed greater than 110% masked features compared to their corresponding lacquered cartridge case scans. Approximately 49% of the cleaned scans were within ±10% of their corresponding lacquered scans, and 29% of the cleaned cartridge cases had less than 90% of masked features their corresponding lacquered cartridge case scans did.

Table 6: Comparing Aperture Shear Toolmarks: Clean Compared to Lacquered

Firearm		Control 1 AS	Control 2 AS	Lacq 3 AS	Cleaned 3 AS	Lacq 4 AS	Cleaned 4 AS	Lacq 5 AS	Cleaned 5 AS
Hi-Point	A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Hi-Point	B	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Ruger	C	100	95	82	84	85	45	43	91
Ruger	D	100	90	39	34	79	95	93	138
Glock	E	100	69	108	95	75	80	127	83
Glock	F	100	109	60	80	80	88	57	57
Skyy	G	100	75	19	26	42	85	59	38
Skyy	H	100	68	96	86	78	77	59	73
Jennings	I	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Jennings	J	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Hi-Point	K	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Hi-Point	L	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Hi-Point	M	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Ruger	N	100	103	154	154	161	137	49	94
Ruger	O	100	111	275	230	65	62	93	114
Ruger	P	100	234	18	19	96	131	84	79
Glock	Q	100	70	64	66	65	66	83	58
Glock	R	100	46	58	61	30	16	32	32
Glock	S	100	122	75	47	92	91	71	79
Skyy	T	100	97	210	243	166	147	160	145
Sccy	U	100	105	81	73	89	77	154	101
Skyy	V	100	42	49	51	91	88	40	35
Jimenez Arms	W	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Bryco	X	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Jennings	Y	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

White: Cleaned values ±10% of Lacquered (49%)
Blue: Cleaned values >110% of Lacquered (22%)
Green: Cleaned values <90% of Lacquered (29%)

F. Discussion

Using excel, a simple statistical test was completed to determine if there was a significant difference between "Control and Lacquered" or "Lacquered and Clean" in both breech-face and aperture shear datasets. The loss in features between the Control 1 and Control 2 breech-face values was quite small at 4.7%. However, when comparing Control 1 to Lacquered and Control 1 to Clean values, the data suggests that there was a significant reduction in tool marks. Because this was a pilot study, the smaller test sets produce high standard deviation values. In larger future studies, these values would be expected to decrease.

Table 7: Toolmark Reduction Summary for Breech-Face Impressions

	Reduction Average	Reduction StdDev
Control 1 → Control 2	-4.7	37.6
Control 1 → Lacquered	62.9	35.4
Control 1 → Clean	74.8	29.5
Lacquered → Clean	11.9	24.5

A Student's t-test was then computed using the breech-face values (Table 8). In this type of evaluation, any p-value below 5% is considered significant. When comparing the difference in masked features of Control to Lacquered scans, the p-value of less than 0.001 suggests that there is a significant loss of breech-face impression toolmarks between the scans. When evaluating the difference in features between the Lacquered and Clean scans, a p-value of 0.034 is close to the 5% threshold but is still considered significant and suggests some possible loss in breech-face impression toolmarks. Larger studies would need to be done to confirm this theory.

Table 8: T-Test P-Value for Breech-Face Impressions

	t-test p-value
Diff btw Control vs Lacquered	< 0.001
Diff btw Lacquered vs Clean	0.034

A reduction summary was then computed for the aperture shear values (Table 9). The Control 1 and Control 2 values were again small (4.3%), as expected, however, the reduction average between the Control 1 and the Lacquered group was only 13.6%, and the Control 1 to Cleaned only showed a decrease by 14.4%, which is much less than the features that were lost in the breech-face comparisons. More detail was lost from impression marks than in striations when lacquered ammunition was used. Again, standard deviation values were large due to the relatively small sample size of this study.

Table 9: Toolmark Reduction Summary for Aperture Shears

	Reduction Average	Reduction StdDev
Control 1 → Control 2	4.3	45.0
Control 1 → Lacquered	13.6	50.5
Control 1 → Clean	14.4	47.2
Lacquered → Clean	0.8	23.4

When a Student's t-test was calculated for the difference between the Control vs Lacquered scans (0.51) and the Lacquered vs Clean scans (0.94), both values were greater than the 5% threshold, suggesting neither comparison shows a statistically significant reduction in aperture shear toolmark transfers (Table 10).

Table 10:T-Test P-Value for Aperture Shears

	t-test p-value
Diff btw Control vs Lacquered	0.51
Diff btw Lacquered vs Clean	0.94

It was recognized that the lacquer may be malleable enough to allow for transfer of some of the toolmark features, but thick enough to prevent the finer details from transferring through to the primer. After evaluating the data sets qualitatively and quantitatively, three trends became evident:

1. Toolmarks visible on a Control scan but not visible on neither the Lacquered nor Cleaned scans are not reliably transferred with Lacquered ammunition.
2. Toolmarks visible on a Lacquered scan but not visible on the Cleaned scan are likely toolmarks only in the lacquer, and may be removed during cleaning.
3. Toolmarks visible on a Cleaned scan but not visible on the Lacquered scan are likely marks that were formed during firing but initially “covered” by lacquer debris. These toolmarks are ‘uncovered’ or ‘revealed’ by cleaning.

Figure 10 depicts theorized trends #1 (red squares) &#2 (yellow circles) below. In the red region in the S1_Control scan, fine parallel lines of the breech-face impression are visible; however these toolmarks are unable to be seen in the S5_Lacquered or S5_Cleaned images because the lacquer prevented them from being transferred at all. In the S5_Lacqered and S5_Cleaned images, which are the same cartridge case, the breech-face pattern appears quite smooth In Figure 10, the yellow circles highlight an example of trend #2, where only the lacquer takes up the toolmarks but they are never transferred to the primer underneath. In the yellow region onS1_Control scan, one can see the aperture shear marks are uniform and well-formed, and although the S5_Lacquered scan also has many striations collected at the end of the aperture shear mark, once cleaning took place, many of those details were lost, as observed in S5_Cleaned.

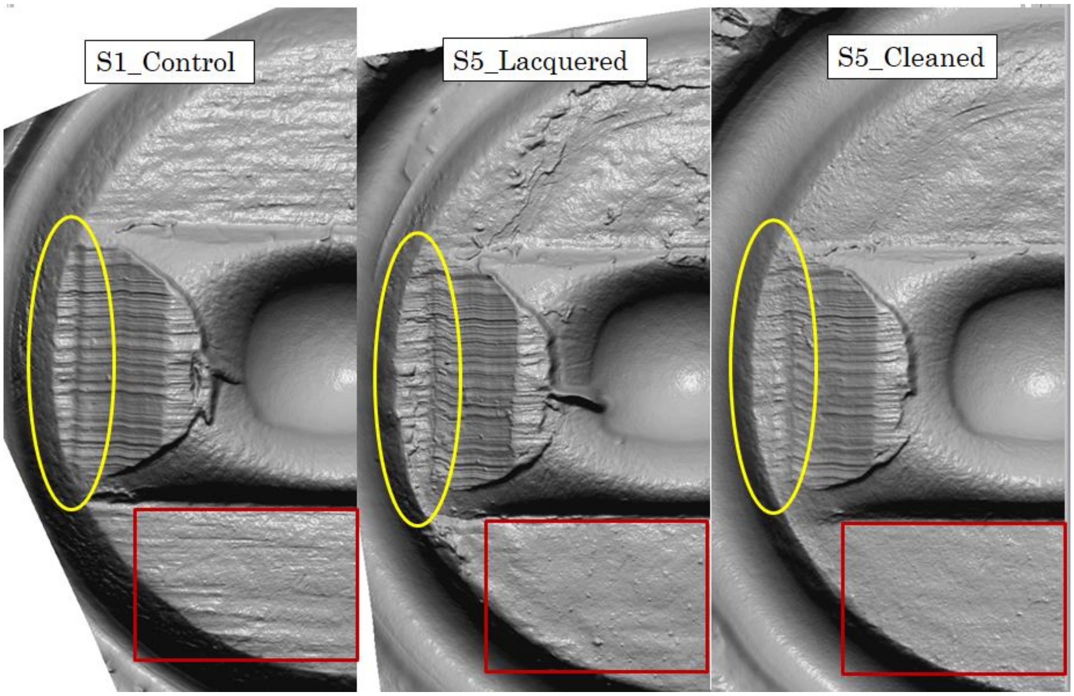

Figure 10: Test-fires collected from Firearm S (Glock) displaying a decrease in transferred toolmarks in the lacquered and cleaned scans.

An additional example of trend #2 can be observed in Figure 11. The heavy lacquer on cartridge case B3_Lacquered obtained many fine toolmarks, however, when the cartridge case was cleaned, as seen in the image on the right (B3_Cleaned), many of the features that could be used to make a comparison were removed and lost.

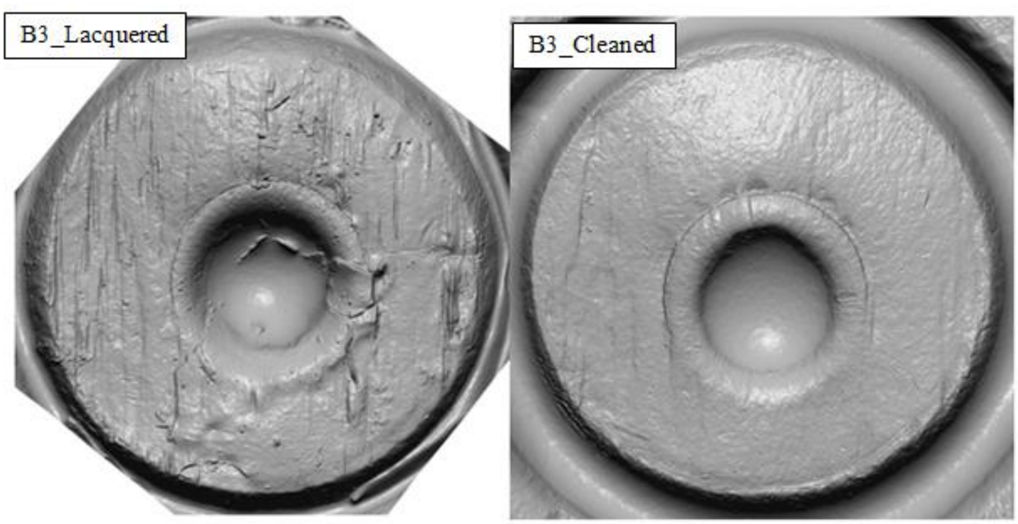

Figure 11: Firearm B (Hi-Point)

Because an aperture shear is created when the edges of the firing pin hole scrape the surface of the primer, striations tend to leave stronger marks than those that are impressed, especially when lacquered ammunition is used. The breechblock essentially pushes any lacquer off any surface it comes into contact with, while a breech face impression tends to crack the lacquer, causing it to chip and flake in a way that might make comparison more difficult. Because of this difference, the quality of striated marks did not seem too greatly affected by the presence of lacquer, but as trend #3 states, this loose lacquer might obstruct examiners from viewing the toolmarks properly.

A soft brush and craft putty where used to clean off all primer surfaces of the cartridge cases prior to scanning, except for the lacquered cartridge cases. This was done purposely to prevent any damage to the toolmarks that may have be left only in the lacquer. It is recognized that this may have led to other debris and loose lacquer adhering to the surface prior to scanning. Figures 12, 13 & 14 provide examples of how removing the lacquer from a cartridge case may improve the quality of the toolmarks.

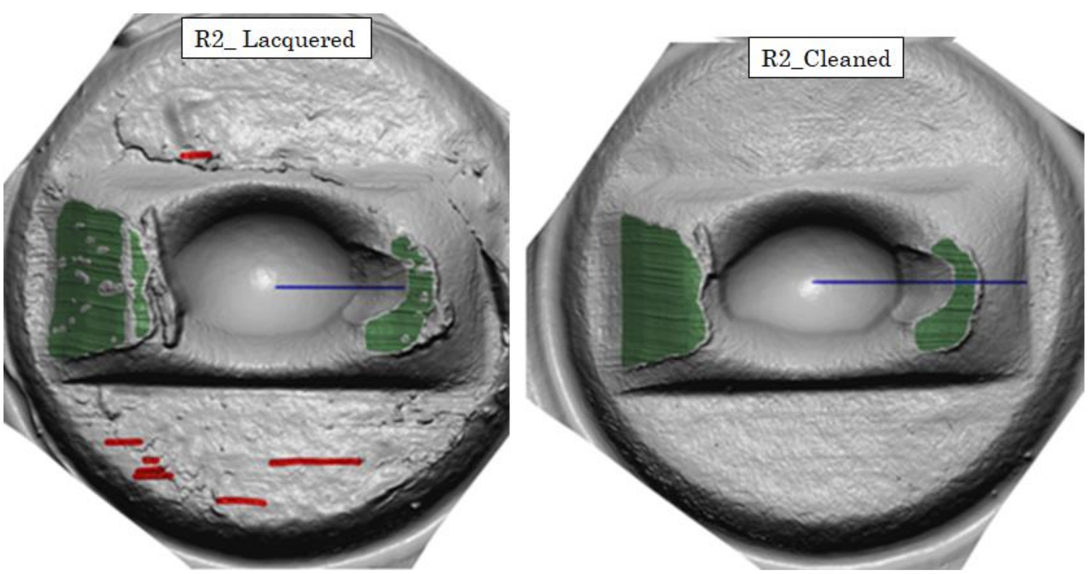

Figure12: Firearm R (Glock) masks before and after cleaning. In this example, the aperture shear surface area (green) increased and the breech-face impression surface area (red) decreased.

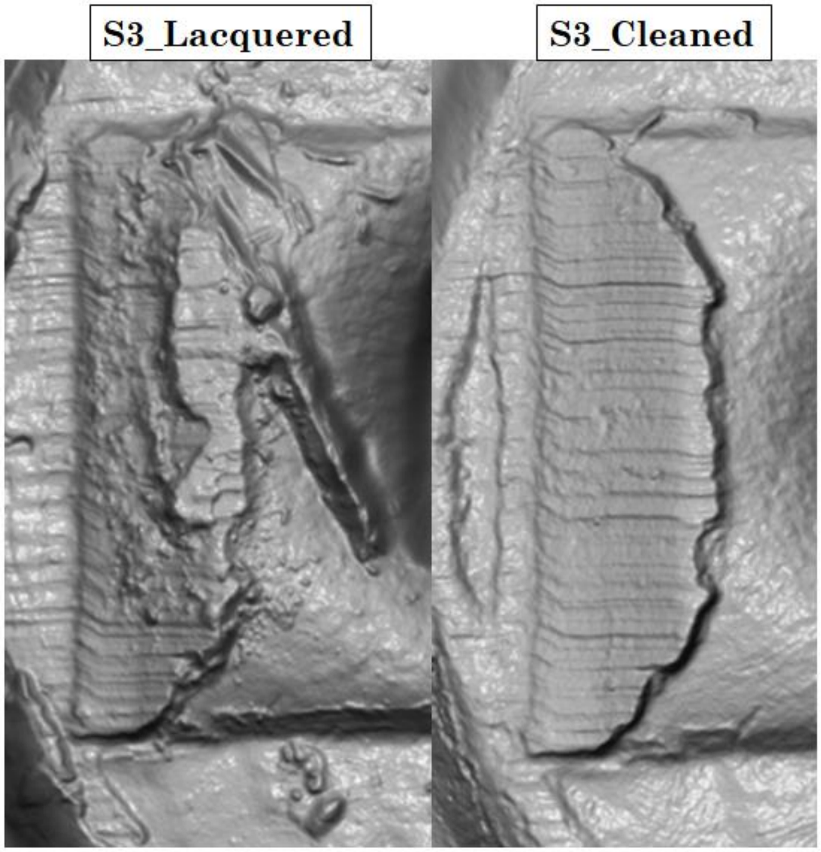

Figure 13: Firearm S (Glock)aperture shears before and after cleaning.

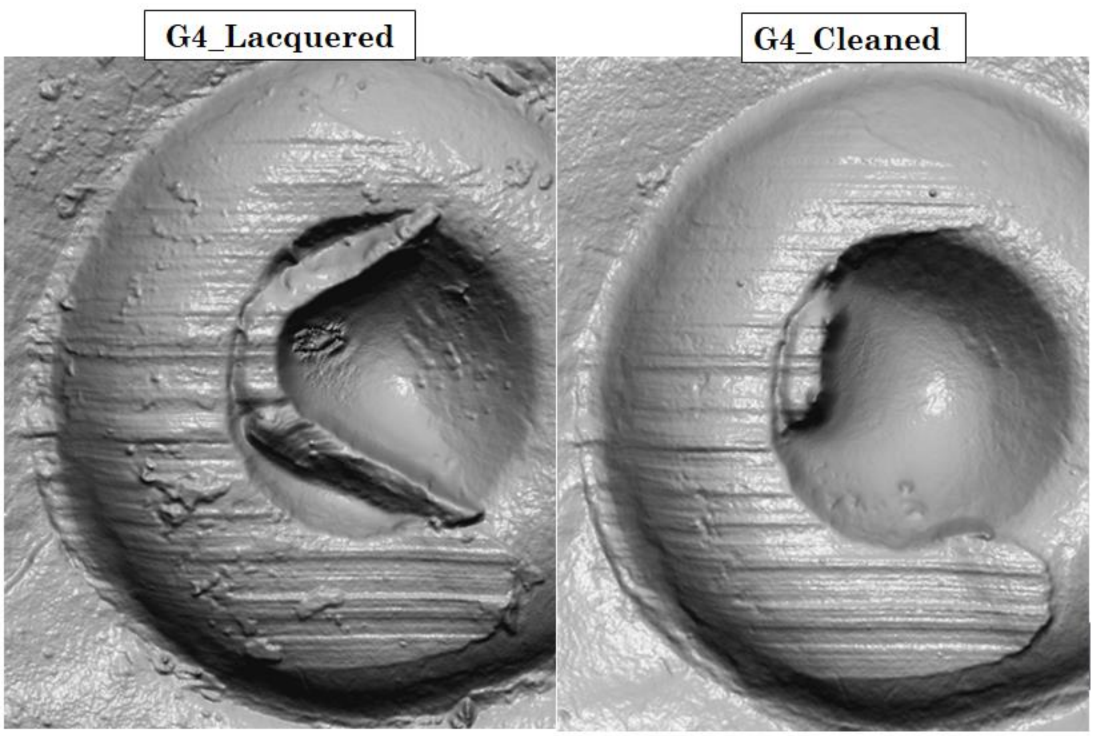

Figure 14: Firearm G (Skyy) aperture shears before and after cleaning.

G. Summary and Conclusions

This investigation was a pilot study meant to explore the effects of lacquered ammunition on the toolmark transfer process. As seen in a previous study, heavily lacquered ammunition has the capability of interfering with the transfer of serial numbers from microstamped firing pins, deeming them illegible even in a highly magnified scanning electron microscope. In this study, several trends were observed:

1. There was a statistically significant difference in breech-face impression marks on the lacquered cartridge cases compared to the control cartridge cases and then even fewer toolmarks were found once cleaning occurred.
2. Some toolmarks were only observed embedded in the lacquer layer; these marks are likely removed during cleaning.
3. Aperture shear marks are less frequently obstructed. This is likely because the raised metal and scrapping forces during cartridge case ejection cause the removal of the lacquer.
4. Some toolmarks were present yet temporarily visually obstructed by lacquer debris. Cleaning was required to reveal these features for visualization.

Based on the results from this investigation, lacquer does interfere with the toolmark transfer process; however, larger studies should be conducted in the future. Because lacquered ammunition is so commonly found in forensics cases, it is highly recommended that Firearms examiners recognize when lacquer is present, so one can properly image and make comparisons both before and after cleaning the primer. This will prevent the loss of any toolmarks that were only left in the lacquer.

Appendix: Breech-face and aperture shear pixels converted to surface area.

Name	BF Pixels	AS Pixels	BF µm²	AS µm²
A1_CONTROL	897571	0	2451202	0
A2_CONTROL	211383	0	2908130	0
A3_CLEANED	364964	0	684880	0
A3_LACQUERED	189437	0	1182483	0
A4_CLEANED	315475	0	613775	0
A4_LACQUERED	78871	0	1022139	0
A4_LACQUERED	139262	0	255542	0
A5_CLEANED	482621	0	451208	0
A5_LACQUERED	1254107	0	1563692	0
B1_CONTROL	1029189	0	4063306	0
B2_CONTROL	529257	0	3334572	0
B3_CLEANED	671451	0	1714792	0
B3_LACQUERED	110626	0	2175501	0
B4_CLEANED	158781	0	358428	0
B4_LACQUERED	159046	0	514450	0
B5_CLEANED	738012	0	515309	0
B5_LACQUERED	20778	109117	2391158	0
C1_CONTROL	22138	100063	67320	353539
C2_CONTROL	0	91733	71727	324204
C3_CLEANED	4724	89200	0	297214
C3_LACQUERED	0	49086	15305	289008
C4_CLEANED	0	93291	0	159038
C4_LACQUERED	0	96961	0	302262
C5_CLEANED	0	46229	0	314153
C5_LACQUERED	44071	164315	0	149781
D1_CONTROL	40852	164397	142790	532380
D2_CONTROL	34635	147883	112217	479142
D3_CLEANED	21157	41313	68548	133854
D3_LACQUERED	0	64583	0	209248
D4_CLEANED	5452	117435	17664	380489
D4_LACQUERED	5506	129057	17839	418144
D5_CLEANED	20643	170106	66883	551143
D5_LACQUERED	0	151889	0	492120
E1_CONTROL	321130	184522	1040461	597851
E2_CONTROL	442047	146648	1432232	475139
E3_CLEANED	0	176338	0	571335
E3_LACQUERED	19095	199013	61867	644802
E4_CLEANED	25727	147263	83355	477132
E4_LACQUERED	33595	137521	108847	445568
E5_CLEANED	3625	203234	11745	658478

E5_LACQUERED	6733	235183	21814	761992
F1_CONTROL	0	438165	0	1419654
F2_CONTROL	0	479148	0	1552439
F3_CLEANED	0	351061	0	1137437
F3_LACQUERED	0	264280	0	856267
F4_CLEANED	0	383618	0	1242922
F4_LACQUERED	0	350408	0	1135321
F5_CLEANED	0	256299	0	830408
F5_LACQUERED	0	249249	0	807566
G1_CONTROL	290117	309187	939979	1001765
G2_CONTROL	222429	225526	720669	730704
G3_CLEANED	0	76659	0	248375
G3_LACQUERED	31335	54810	101525	177584
G4_CLEANED	22712	247357	73586	801436
G4_LACQUERED	33007	121257	106942	392872
G5_CLEANED	46777	109995	151557	356383
G5_LACQUERED	100081	170828	324262	553482
H1_CONTROL	24	287574	77	931739
H2_CONTROL	108	209659	349	679295
H3_CLEANED	0	239524	0	776057
H3_LACQUERED	0	265178	0	859176
H4_CLEANED	0	213482	0	691681
H4_LACQUERED	0	216551	0	701625
H5_CLEANED	0	203541	0	659472
H5_LACQUERED	0	164653	0	533475
I1_CONTROL	101182	0	327829	0
I2_CONTROL	80734	0	261578	0
I3_CLEANED	78641	0	254796	0
I3_LACQUERED	89730	0	290725	0
I4_CLEANED	82546	0	267449	0
I4_LACQUERED	58652	0	190032	0
I5_CLEANED	83462	0	270416	0
I5_LACQUERED	83931	0	271936	0
J1_CONTROL	36428	0	118026	0
J2_CONTROL	78241	0	253500	0
J3_CLEANED	61951	0	115344	0
J3_LACQUERED	35600	0	115344	0
J4_CLEANED	22947	0	74348	0
J4_LACQUERED	30762	0	99668	0
J5_CLEANED	0	0	0	0
K1_CONTROL	5303809	0	17184341	0
K2_CONTROL	184961	0	599273	0
K3_CLEANED	47538	0	21131	0

K3_LACQUERED	27484	0	154023	0
K4_CLEANED	28732	0	89048	0
K4_LACQUERED	30812	0	93091	0
K5_CLEANED	22475	0	99830	0
K5_LACQUERED	498614	0	72819	0
L1_CONTROL	689605	0	1615509	0
L2_CONTROL	0	0	2234320	0
L3_CLEANED	95514	0	309465	0
L3_LACQUERED	216067	0	700057	0
L4_CLEANED	158668	0	514084	
L4_LACQUERED	181779	0	588963	0
L5_CLEANED	77710	0	251780	0
L5_LACQUERED	123774	0	401027	0
M1_CONTROL	791171	0	2563394	0
M2_CONTROL	1312278	0	4251780	0
M3_CLEANED	137032	0	443983	0
M3_LACQUERED	409204	0	1325820	0
M4_CLEANED	167350	0	542214	0
M4_LACQUERED	422966	0	1370409	0
M5_CLEANED	284616	0	922155	0
M5_LACQUERED	470214	0	1523493	0
N1_CONTROL	26301	84781	85215	0
N2_CONTROL	24272	87489	78641	0
N3_CLEANED	10978	130660	35568	274690
N3_LACQUERED	30978	130704	100368	283464
N4_CLEANED	0	116507	0	423338
N4_LACQUERED	18009	136115	58349	423480
N5_CLEANED	0	79287	0	377482
N5_LACQUERED	0	41827	0	441012
O1_CONTROL	29682	103549	96169	79286
O2_CONTROL	29106	88008	94303	285146
O3_CLEANED	8140	240267	26373	335498
O3_LACQUERED	30965	284843	100326	303458
O4_CLEANED	26414	64310	85581	778465
O4_LACQUERED	33916	67064	109887	922891
O5_CLEANED	8738	118337	28311.12	208364
O5_LACQUERED	17969	96217	58219	217287
P1_CONTROL	0	103337	0	383411
P2_CONTROL	0	242200	0	311743
P3_CLEANED	0	19317	0	334811
P3_LACQUERED	0	18996	0	784728
P4_CLEANED	0	136227	0	62587
P4_LACQUERED	0	99187	0	61547

P5_CLEANED	0	81304	0	441375
P5_LACQUERED	0	87038	0	321365
Q1_CONTROL	263465	214662	853626	263424
Q2_CONTROL	281015	155350	910488	282003
Q3_CLEANED	0	140767	0	695504
Q3_LACQUERED	101156	135289	327745	503334
Q_Q4_CLEANED	103464	142482	335223	456085
Q4_LACQUERED	79582	137495	257845	438336
Q5_CLEANED	47870	122180	155098	445483
Q5_LACQUERED	62662	177908	203024	461641
R1_CONTROL	302511	370025	980135	576421
R2_CONTROL	318353	169822	1031463	395863
R3_CLEANED	0	224182	0	1198881
R3_LACQUERED	31474	213292	101975	550223
R4_CLEANED	0	58631	0	726349
R4_LACQUERED	86726	112745	280992	691066
R5_CLEANED	25032	119350	81103	189964
R5_LACQUERED	102707	119546	332770	365293
S1_CONTROL	188473	268512	610652	386694
S2_CONTROL	180841	326861	585924	387329
S3_CLEANED	0	126057	0	869978
S3_LACQUERED	0	20226	0	1059029
S4_CLEANED	0	270716	0	408424
S4_LACQUERED	14311	246718	46367	65532
S5_CLEANED	0	211199	0	877119
S5_LACQUERED	0	191134	0	799366
T1_CONTROL	12865	275952	46367	684284
T2_CONTROL	7651	122120	44976	619274
T3_CLEANED	11	345083	35	894084
T3_LACQUERED	11	283452	35	395668
T4_CLEANED	0	305080	0	988459
T4_LACQUERED	0	205773	0	666704
T5_CLEANED	5	400726	16	1298352
T5_LACQUERED	0	326054	0	1056414
U1_CONTROL	341809	323088	1107461	1046805
U2_CONTROL	499607	256902	1618726	832362
U3_CLEANED	386341	257267	1251744	1046805
U3_LACQUERED	390985	260239	1266791	843174
U4_CLEANED	328591	270764	1064634	877275
U4_LACQUERED	426149	287135	1380722	930317
U5_CLEANED	285377	475383	924621	1540240
U5_LACQUERED	313430	497484	1015513	1611848
V1_CONTROL	192299	503568	623048	1631560

V2_CONTROL	192299	503568	617252	693343
V3_CLEANED	22602	258261	73230	836765
V3_LACQUERED	38017	244878	123175	793404
V4_CLEANED	20019	440144	64861	1426066
V4_LACQUERED	53531	458658	173440	1486051
V5_CLEANED	19692	175980	63802	570175
V5_LACQUERED	45902	199342	148722	645868
W1_CONTROL	59831	0	193852	0
W2_CONTROL	63080	0	204379	0
W3_CLEANED	27713	0	89790	0
W3_LACQUERED	38501	0	124743	0
W4_CLEANED	9745	0	31573	0
W4_LACQUERED	7690	0	24915	0
W5_CLEANED	13830	0	44809	0
W5_LACQUERED	12406	0	40195	0
X1_CONTROL	184302	0	597138	0
X2_CONTROL	126303	0	409221	0
X3_CLEANED	44004	0	142572	0
X3_LACQUERED	52334	0	169562	0
X4_CLEANED	70009	0	226829	0
X4_LACQUERED	117878	0	381924	0
X5_CLEANED	91171	0	295394	0
X5_LACQUERED	101269	0	328111	0
Y1_CONTROL	133185	0	431519	0
Y2_CONTROL	139641	0	452436	0
Y3_CLEANED	0	0	0	0
Y3_LACQUERED	0	0	0	0
Y4_CLEANED	40386	0	130850	0
Y4_LACQUERED	36081	0	116902	0
Y5_CLEANED	39340	0	127461	0
Y5_LACQUERED	41585	0	134735	0

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VITA

NAME:	Nicole Groshon
EDUCATION:	B.A., Forensic Science, Loyola University, Chicago, Illinois 2015
	M.S., Forensic Science, University of Illinois at Chicago, Chicago, Illinois 2020
PROFESSIONAL EXPERIENCE:	Department of Public Safety Crime Laboratory, Forensic Scientist Houston, Texas, March 2020 - Present
	Cadre Forensics, Intern Chicago, Illinois, January 2019- January 2020
	McCrone Associates, Cleanroom Microscopist Westmont, Illinois, January 2015 - August 2018
INVITED TALKS:	The effects of lacquered ammunition on toolmark transfer. The Association of Firearm and Tool Mark Examiners, FBI Academy. Quantico, Virginia 2019
ADDITIONAL TRAINING:	Scanning Electron Microscopy Hooke College of Applied Sciences, Westmont, IL 2017
	Polarized Light Microscopy Hooke College of Applied Sciences, Westmont, IL 2015
	Microscopic Particle Handling: Particle Isolation, Manipulation, and Mounting Hooke College of Applied Sciences, Westmont, IL 2015