

Evaluation of Barrel Wear Caused by Polymer Coated Bullets

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Thesis submitted
to the Forensic Science Institute
at the University of Central Oklahoma

in partial fulfillment of the requirements for the degree of

Master of Science in
Forensic Science

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Edmond, Oklahoma
2026

Keywords: *Forensic Science, Firearms and Toolmarks, Barrel Wear, Glock Marksman Barrel (GMB), Total Synthetic Jacket (TSJ), Full Metal Jacket (FMJ), Consecutive Matching Profile Segments (CMPS)*

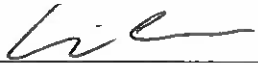
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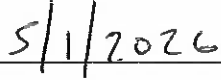
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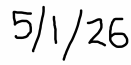
M.S. DEGREE THESIS

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M.S. degree in Forensic Science

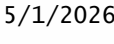

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ABSTRACT

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Forensic firearm analysis resides on the principle that each firearm is capable of imparting individual characteristics on ammunition components. Individual characteristics can be used to link a bullet or cartridge case back to the firearm which fired it. Bullets acquire these markings from the interior features of the barrel, which are subject to change over time due to wear caused by repeated firing and possible damage. Among various ammunition available, polymer-coated ammunition, such as Federal Total Synthetic Jacket (TSJ) ammunition, has recently gained popularity for its potential to reduce lead exposure and firearm fouling. However, while existing literature documents barrel wear caused by traditional ammunition, the forensic implications of TSJ ammunition remain under-researched, particularly regarding its impact on barrel wear and the visibility of individual toolmarks used for firearm identification. The goal of this study was to determine whether Federal Premium's Total Synthetic Jacket (TSJ) ammunition causes less barrel wear and degradation of individual characteristics compared to Full Metal Jacket (FMJ) ammunition over the course of 500 shots. Two Glock 19 Gen5 caliber 9mm Luger pistols equipped with Glock Marksman Barrels (GMBs) were used, one firing exclusively FMJ bullets (known as the control), and the other firing TSJ rounds while also firing an FMJ round every 10th shot (known as the experimental). Of 1000 fired bullets, 102 were collected for analysis. Three-dimensional scans of the land engraved areas (LEAs) were captured using the Cadre Forensics TopMatch-3D system. The Congruent Matching Profile Segments (CMPS) algorithm, integrated into the Cadre software, was employed to compare the LEAs quantitatively. A total of 612 LEA scans were collected and examined. Results have indicated that the polymer-coated TSJ bullets led to increased wear of the barrel surface, significantly reducing the clarity and frequency of striated toolmarks over successive firings. In contrast, FMJ rounds maintained a higher level of individual characteristic retention. The Kwiatkowski Phillips Schmidt Shin (KPSS) time series test was used to test the stationarity in the dataset. Results suggest that TSJ ammunition may contribute to increased barrel wear and does have a significant effect on the clarity and frequency of striated toolmarks across successive firings. In contrast, FMJ rounds do contribute to barrel wear, while also maintaining striated toolmarks necessary for forensic comparison.

Acknowledgements

I would like to acknowledge individuals for their knowledge and guidance throughout the process of creating my thesis.

I would like to thank the University of Central Oklahoma (UCO) Student Research, Creative, and Scholarly Activities (RCSA) Grant for their financial support of this project. Additionally, I would like to thank the Association of Firearm and Toolmark Examiners (AFTE) Scholarship Committee for graciously awarding me an AFTE Scholarship. To my thesis committee and committee chair thank you for your unwavering support and assistance throughout the creative process of this journey. To my fellow Graduate students namely Britlyn Eckerd and Angela Gonzales-Bueno thank you both for making the time as a graduate student not only fun but interesting. To my fellow fraternity brothers thank you all for the times shared and the memories made. Additionally, thank you all for assisting me in the creative writing process. To the FSI faculty thank you all the continued support throughout my undergraduate and graduate studies. Finally, to my family and girlfriend thank you for encouraging me to step outside my comfort zone and continue to challenge myself throughout this academic journey.

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1. Introduction

Forensic firearms examiners attempt to determine whether a piece of firearms evidence (a fired cartridge case or a bullet recovered from a crime scene) was fired by a suspect firearm. To make these determinations examiners create exemplars from the suspect firearm. An exemplar could be a test fired cartridge case or a test fired bullet that is produced in a lab. These exemplars serve as known references for comparing to unknowns recovered at the crime scene. The results of these comparisons are classified as an Identification, Elimination, Inconclusive, or Unsuitable[1, 2]. When producing an exemplar, examiners should select ammunition similar to that found at the crime scene, as variations in component materials or pressure can affect the appearance of toolmarks [3]. It is important to note that the examiners are not responsible for determining who fired the weapon.

1.1 Elements of Firearms Evidence Analysis

Firearms examiners are tasked with linking suspect firearms to recovered firearms evidence. To understand how examiners can conclude an identification, a basic understanding of how toolmarks are created is necessary. The interaction between a hard surface and a soft surface while in motion creates a striated toolmark [4]. These striated toolmarks serve as the foundation for firearms examiners when making comparisons with bullets.

An examiner can observe three types of characteristics during the examination process: class characteristics, subclass characteristics, and individual characteristics. Class characteristics are predetermined before manufacturing and distinguish a group of firearms [4-6]. For example, older Glock pistols have an elliptical shaped firing pin, whereas Ruger pistols have a hemispherical shaped firing pin. These characteristics can be used as criteria for elimination from other firearms. However, it is important to note that some firearms may share the same class characteristics since they likely share similar manufacturing techniques.

Subclass characteristics are features created during the manufacturing process that remain consistent among objects produced by the same tool at a similar stage of wear. Unlike

class characteristics, these features are not predetermined before manufacturing and are more restrictive, applying to a smaller subset within a given group. Subclass characteristics result from imperfections, defects, or gradual wear in the manufacturing tool, meaning they can change over time [4-6]. For example, a worn rifling tool may leave unique surface patterns on a series of barrels before being replaced or retooled. These patterns would be shared by some, but not all, barrels produced during that period. Since subclass characteristics can sometimes resemble individual characteristics, examiners must carefully distinguish between the two to avoid misidentifications.

Individual characteristics are unique tool marks that result from random imperfections or irregularities on a tool's surface. These imperfections occur during the manufacturing process and may develop over time due to use, corrosion, or damage [4-6]. Because they are specific to a single tool, they serve as the basis for firearm evidence comparison and source determination. For example, the barrel of a firearm may develop microscopic nicks or wear patterns through repeated use. When a bullet is fired, these unique markings are imprinted onto its surface, allowing firearms examiners to identify a fired bullet to a specific firearm.

Traditionally, the main instrument used by a firearms examiner is a comparison microscope to observe, evaluate, and for source determination of toolmarks. A comparison microscope consists of two microscopes that are bridged optically allowing the examiner to view both stages at the same time under the same magnification [4]. Examiners can utilize one stage for an unknown and the other for a known exemplar. However, with the introduction of the 2016 President's Council of Advisors on Science and Technology (PCAST) report establishing a lack in scientific validity and subjectivity in firearms analysis, recommendations were made to convert firearms analysis from a subjective method to an objective method [7]. Since, conventional means of examination have been criticized for being subjective in nature, techniques that attempt to quantify results have been created. Consecutive Matching Profile Segments (CMPS) method takes a section of a three-dimensional (3D) scan from either a cartridge case or a fired bullet and then correlates sections from the reference profile to other scanned profiles to produce similarity scores. Companies like Cadre Forensics utilize an algorithm similar to CMPS with their TopMatch-3D.

1.2 Parts of a Firearm

When discussing firearms, it is important to know and understand their parts and manufacturing methods. There is one main component within firearms that produces marks on a projectile (bullet) which is the barrel. As shown in Figure 1.1, the barrel contains rifling

which imparts spin to the bullet. Rifling consists of lands and grooves and can twist either left or right. In the barrel depicted, we can see that it has six lands and grooves and is a right twisting barrel. The raised portions in the barrel (the lands) create what is known as land engraved areas (LEAs) on a fired bullet. In contrast, the lowered portions in the barrel (the grooves) create groove engraved areas (GEAs). In Figure 1.2, a fired bullet is shown with both LEAs and GEAs which are used for forensic comparison between known test fired bullets and unknown bullets recovered from crime scenes.

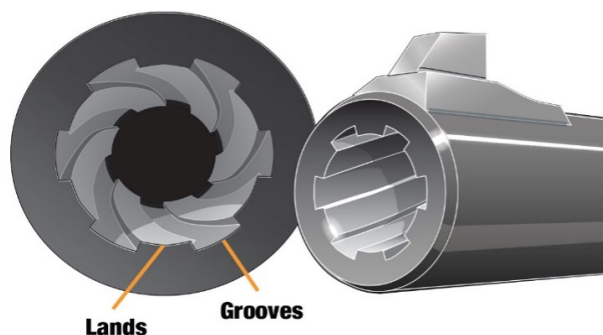


Figure 1.1: Conventionally rifled barrel depicting the lands and grooves.



Figure 1.2: Fired bullet depicting both LEAs (shown in red) and GEAs (shown in blue).

Generally, the LEAs are preferred for comparison due to their unique striations and lower potential for subclass characteristics than GEAs [8-11]. While GEAs still hold forensic value, the inclusion of subclass characteristics due to the manufacturing method used can interfere with the comparison of bullets [11, 12]. The rifling of the barrel is dependent on the firearm company's desired manufacturing processes. Differing processes play a large role in what type of marks are left behind on a projectile. There are generally two main types of rifling for handguns: conventional rifling and polygonal rifling. Conventional rifling consists of

lands and grooves that have well defined shoulders. Polygonal rifling also consists of lands and grooves; however, the shoulders are much less defined. Seen in Figure 1.3 is a comparison between a conventional barrel and a polygonal barrel. Conventional rifling, featuring lands and grooves, is more common and imparts a greater number of individual characteristics. Conversely, polygonal rifling, utilized by some manufacturers, features hills and valleys that are less conducive to imparting individual characteristics, thereby complicating the forensic comparison of fired bullets.

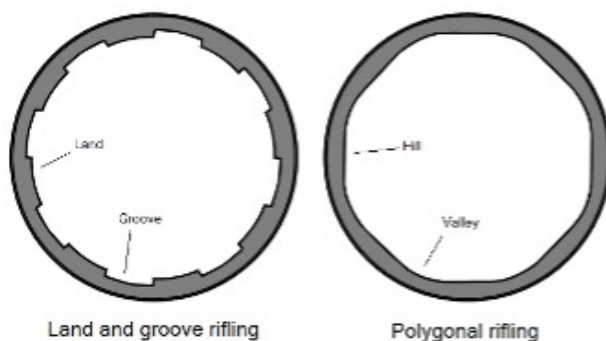


Figure 1.3: Comparison between conventionally rifled barrel and a polygonally rifled barrel.

Both types of barrel manufacturing methods start the same way, with a barrel blank or a metal rod (typically steel) which is then drilled. After a hole has been drilled through the length of the barrel, a smoothing process known as reaming is performed to produce an accurate diameter for the specific barrel. During reaming, the cutting tool moves through the barrel leaving circular toolmarks. These marks transfer onto a fired bullet, appearing as parallel striations on its surface. Following reaming, the barrel then has to be rifled. There are various methods that can be used to rifle a barrel, however the most popular for pistols are button rifling, broach rifling, and hammer forging [4, 5, 13, 14].

- **Button rifling** is a cold working method where metal is not removed from within the barrel (see figure 1.4). For this method, the button is attached to a hydraulic press and is then pushed through the barrel forming the grooves in the barrel, while using lubricants to minimize heat caused by friction. It is important to note that since there is no metal being removed by this process a highly polished button with no damage may not produce major unique marks.

Companies such as Armscor, Bushmaster, Carl Walther, Colt, Eddy, Hi-Point, High Standard, Iver Johnson & Painfield Carabine, Jordan Armament & Weapon Systems



Figure 1.4: Rifling button.

(JAWS), John Slough of London (JSL), Kel-Tec, Kimber, Lorcin, Lothar Walther, Marlin, Mossberg, Sarsilmaz, Savage Arms, Shilen, Springfield Armory, Stallard Arms, Sterling Arms, STI International, Taurus, Walther, Wilson Arms, and Winchester are well-known manufacturers that use button rifling [4, 14-16].

- **Broach rifling** is a form of cut rifling, and this method utilizes a rod with multiple buttons with teeth at varying heights which progressively remove material forming grooves (see figure 1.5). To introduce twist in the barrel, a rotating clamp is used to turn the barrel while it is being broached.



Figure 1.5: Rifling broach.

Companies such as Berretta, Bernardelli, Bushmaster, Briley, Colt, Dan Wesson, F.B. Radom, Iver Johnson & Painfield Carabine, Jimenez Arms (formerly Bryco Arms), Kimber, Mossberg, Para Ordinance (Para USA), Rohrbaugh, Ruger, Sarsilmaz, Smith

& Wesson, Star, Wilson Arms, and Winchester are well-known manufacturers that use broach rifling [4, 14-16].

- **Hammer forging** is a cold forging method used which inserts a piece of metal with the impression of the rifling, known as a mandrel, into the barrel (see figure 1.6). Once the piece is inserted into the barrel, the outer surface of the barrel is then hammered imparting the impression of the rifling onto the barrel. Hammer forging a barrel does have two main drawbacks, those being that the bore of the barrel will be slightly larger than expected as to fit the mandrel, and secondly the initial barrel length will be shorter than the finished barrel length due to the hammering. However, the advantages of hammer forging are a reduction in metal fouling, and this rifling is considered a more accurate barrel due to the intimate contact in the barrel. Hammer forging unlike alternative rifling methods is used to make polygonal rifling.



Figure 1.6: Rifling mandrel.

Companies such as Arcus, CZ, Fabrique Nationale (FN) Herstal, Hekler & Koch (H&K), Glock, Lothar Walther, Makarov, Remington, Ruger, Sabatti, Sarsilmaz, SIG Sauer, Springfield Armory, Steyr, Weatherby Vektor, and Zastava Arms are well-known manufacturers that use hammer forged rifling [4, 14-16].

- **Glock Marksman Barrel (GMB)**, was introduced around 2014 and implemented in 2017 for consumers. The GMB features a hammer forged polygonal barrel with rifled “micro land” shoulders along the sides of each hill and valley section, which is depicted in figure 1.7 [17-19]. In comparison to a traditional hammer forged barrel, the GMB’s mandrel includes grinded rails which result in the “micro land” shoulders on the manufactured barrel [20].

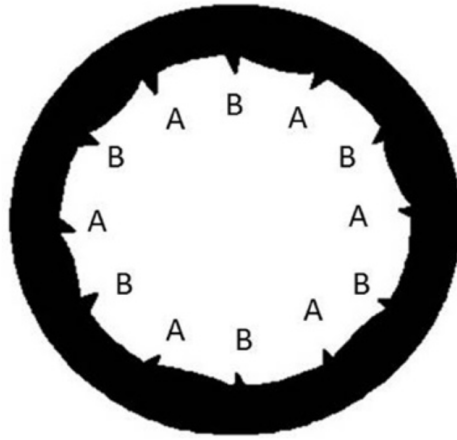


Figure 1.7: Demonstration of GMB, where sections A and B mark the rifled "micro land" sections.

Multiple researchers have published articles analyzing the marking potential and wear patterns of these new barrels. Previous publications have stated Glocks intentions in implementing the prior Enhanced Bullet Identification System (EBIS) barrel and the latest version GMB to address the need to produce a "readily identifiable" bullet. Multiple researchers have published articles analyzing the marking potential and wear patterns of these new barrels. For example, one study evaluating individual and sub-class characteristics of GMBs found that the striation pattern from bullet one for a given barrel was repeated and identifiable for bullet two [19]. Additionally, when the bullets were intercompared between barrels, only bullets from the same barrel could be identified, there were no misidentifications between barrels.

1.3 Ammunition Types

When looking at ammunition types there is a plethora of choices to be made. Brand, bullet grain (weight), bullet composition, style of bullet, and type of cartridge case are all considerations that have to be made when purchasing ammunition. While law enforcement may use a certain type of ammunition for training purposes, they may not use the same for daily patrol. Similarly for the public, hunters, or competition shooters all may use completely different ammunition to fit their intended use(s) and targets. Generally, some of the most popular choices for pistol ammunition are Full Metal Jacket (FMJ) and Jacketed Hollow Point (JHP) [4].

FMJ ammunition is one of the most commonly used bullet types. Generally, a lead alloy core is encompassed with a metal jacket and an exposed base. Typically, the metal jacket is copper but can be made of either brass, copper or alternative copper alloys. The main function of the metal jacket is to reduce metal fouling of the barrel grooves which requires more cleaning and can reduce accuracy. By covering the lead projectile with a harder metal this fouling is reduced. FMJ projectiles are most commonly found in a round nosed variant but can be flat nosed as well [4]. Seen in figure 1.8 is a picture of a FMJ cartridge compared to a Jacketed Hollow Point (JHP) cartridge.



Figure 1.8: Comparison between Full metal jacket (FMJ) and Jacketed hollow point (JHP) ammunition.

Copper-plated ammunition is an alternative to the traditional jacketed ammunition. Copper-plated ammunition utilizes electrochemical plating to apply a thin layer of copper to the lead core of the bullet. Benefits of copper-plated ammunition, such as those marketed by CCI, are similar to those of traditional FMJ ammunition, which include the ability to reduce fouling in the barrel and reducing lead expose for the for the shooter. Although, the disadvantages of copper-plated bullets are the susceptibility of the plating to be stripped of by the rifling. The layer of copper used on copper-plated bullets extremely thin, due to the minimal amount of copper used for plating these bullets, when fired the aggressive interaction between barrel rifling tends to strip away this copper plating [4].

Jacketed hollow point (JHP) ammunition features a traditional lead core and a copper jacket, however JHP ammunition has a hollow cavity in the nose and the base of the bullet is enclosed. This cavity allows the projectile to expand or mushroom on impact which releases all of the bullets kinetic energy within the target allowing the projectile to stay in the desired target. Figure 1.9 shows a JHP projectile alongside a cross-section view and an expanded JHP projectile to illustrate its appearance upon impact. To control the expansion of the bullet, manufacturers will often score the projectile so it will react in a more predictable

manner. Ammunition companies have also made efforts to individualize their specific bullets by adding colored polymer inserts into the cavity. These types of bullets are typically used for hunting and self-defense applications [4].



Figure 1.9: Expanded JHP Projectile.

Solid copper ammunition is made from either solid copper or a solid copper alloy with no lead core. As the name suggests, this ammunition is made from a solid piece of copper. The solid copper construction of the ammunition leads to less fragmentation upon impact. The solid copper ammunition is becoming more prevalent in hunting due to the move to reduce lead exposure [21]. Solid copper hollow point ammunition is also available for purchase. Unlike traditional JHP ammunition, solid copper hollow points are constructed out of solid copper and do not possess a lead core. Solid copper ammunition does require more expensive manufacturing process and are therefore reserved for high end ammunition types [4].

In 2016, Federal Premium Ammunition released a polymer jacketed line of projectiles known as Federal Syntech. These projectiles have been on the rise due to their limited lead composition, while they do still have a lead core Federal utilizes a lead free primer [22]. The revitalized form of ammunition is known as Total Synthetic Jacket (TSJ) or polymer coated bullets. Ammunition with jackets consisting of materials other than metal is not new to the market [4, 23, 24]. In the 1970's Smith and Wesson created the Nyclad line of ammunition which was a nylon coating over a lead core [23, 24]. The nylon coating was said to have reduced the lead exposure to shooters at indoor ranges. Federal Premium Ammunition bought the rights to Nyclad and began producing them until later developments were made. The polymer coated "Syntech" cartridges contain a lead core bullet with a proprietary polymer coating. Federal now offers polymer-coated ammunition in four different configurations: Syntech Range and Syntech Action Pistol, which are red; Syntech Defense, which is blue; and Syntech Training Match, which is purple [25].

Since this ammunition is polymer coated it prevents metal-on-metal contact within barrel, which would theoretically reduce barrel wear. Additionally, this ammunition is supposed to reduce heat due to friction. It is important to note that researchers have established forensic concerns regarding this ammunition type. Because the TSJ ammunition uses a polymer jacket, these bullets typically display general rifling characteristics (GRC) such as lands, grooves, and direction of twist. However, individual characteristics are not always imparted or visible to the examiner, which can make forensic comparison challenging as shown in Figure 1.10 [23, 24]. The lack of individual characteristics was attributed to the possibility of the polymer compound melting during the firing process. It was also noted that there was a uniform pitting on the surface of the bullets.



Figure 1.10: comparison of a fired FMJ projectile showing identifiable striations (highlighted in blue boxes), and a fired TSJ projectile, which exhibits uniform pitting and partial surface melting (highlighted in gray boxes)

Although ammunition manufacturers, like Federal, make this ammunition on a large scale, individual reloaders can also apply polymer coatings to their own ammunition at home. Companies like Hi-Performance manufacture a Hi-Tek bullet coating that, when mixed, can be used to coat projectiles [26].

1.4 Barrel wear

Bullets recovered at crime scenes can serve as important forensic evidence for firearms examiners. When a firearm is discharged, fired projectiles acquire both class and individual characteristics from the barrel. For example, class characteristics of a barrel include the type of rifling, number and widths of lands and grooves, or the direction of twist. Individual characteristics would include the specific imperfections of the barrel caused from both the manufacturing processes used as well as use of the firearm over time. These individual characteristics within the barrel are referred to as striations, and studies have demonstrated that bullets fired from separate barrels do not have the same striations [27-29]. Over time, the individual characteristics inside a firearm's barrel can wear down, posing challenges for the forensic identification of firearms evidence.

There have been numerous studies examining the persistence of barrel characteristics over successive fire which have shown that over time the toolmarks within the barrel change. For example, one study examined the individual characteristics left on marks from a 9mm Ruger P89 pistol [30]. For their study, 1,000 Winchester 9mm Luger caliber cartridges which contained full metal jacket bullets were used. The first ten fired bullets and cartridge cases were collected, as well as every 25th fired bullet and cartridge case. Each bullet and cartridge case were then compared to the first bullet and cartridge case. Comparisons were performed by pattern matching using a comparison microscope to identify sufficient agreement of individual characteristics or striations. Bullet comparisons were also verified by a second examiner. The authors observed that although there were differences in striae throughout the bullets, each bullet was able to be identified to the first bullet through pattern matching. Additionally, the authors state that bullets fired closer in sequence tend to have more frequent and longer striations than those further apart in the sequence.

Another study examined the ability of firearms examiners to identify bullets from 10 consecutively manufactured 9mm Ruger pistol barrels [29]. The study used Winchester 9mm Luger caliber with full metal jacketed ammunition. A total of 240 test sets were prepared which consisted of both known (or control) and unknown (or experimental) sets. The control sets were comprised of 10 bullets from each barrel, whereas the unknown sets were comprised of 15 bullets with at least one from each barrel but no more than three bullets from one barrel. The 240 test sets were then sent out to firearms laboratories, universities and researchers around the world. The participants were tasked with identifying the unknown bullets to one of the known bullets. The results showed that out of the 7,605 unknown bullets a total of 3 were marked "inconclusive" due to damage. An additional five of the bullets

were inconclusive by two trainee examiners. The participants were able to correctly identify the remaining 7,597 unknown bullets to their known counterparts. The authors noted that the identification process had a low error rate despite complications due to bullet damage. In addition, the study disproved various statements about examiners inability to identify bullets from consecutively rifled barrels.

An additional study, examined the effects of solid copper bullets on barrel wear [31]. This study utilized 500 rounds of Barnes Ammunition VOR-TX 9mm Luger caliber solid copper bullets. The barrel characteristics were profiled by collecting the first and last ten fired bullets. Throughout the course of fire every tenth bullet was collected to view the changed of the barrel throughout the study. The firearm used for the study was a Glock 19 Gen5 pistol, caliber 9mm Luger. This firearm traditionally has a polygonally rifled barrel, however, with the Gen 5 Glock models the new Glock Marksman Barrel (GMB) was introduced. Each of the 68 collected bullets were then scanned on the Cadre Forensics Versa system which utilizes TopMatch software provides an objective and quantitative approach to firearm analysis. The results showed that on bullet 001 there were very prominent striations, but by bullet 500 the striations almost completely disappear. Features from the bullet 001 began softening between bullets 200 and 300, however more noticeable changes were noted around bullet 400. Thus, comparison between bullet 001 and 500 did not result in an identification.

This project is significant to the field of Firearm and Toolmark Identification because it explores the impact of different ammunition types on forensic firearms analysis, specifically how FMJ and TSJ bullets influence tool mark consistency over successive firings. Given the increasing use of TSJ ammunition and its potential to alter barrel characteristics differently than FMJ ammunition, understanding its effects is crucial for forensic examiners. The study's focus on Glock 19 Gen 5 barrels, a widely used firearm, enhances its practical relevance, as law enforcement agencies and forensic labs frequently encounter this firearm. By analyzing how tool marks evolve with different ammunition types, this research aims to improve the accuracy and reliability of firearm identifications in criminal investigations. Due to the polymer jacketing and the claims that Federal premium has made with regard to their TSJ ammunition. We hypothesize that Federal Premium's TSJ ammunition will lead to decreased barrel wear when compared to traditional FMJ ammunition.

2. Methods

2.1 Firearm and Barrel

A Glock 19 Gen5 pistol chambered in 9mm Luger was chosen due to its widespread use. According to GunBroker.com’s 2024 annual report, the Glock 19 ranked as the third highest-selling handgun [32]. Additionally, the Bureau of Alcohol, Tobacco, Firearms, and Explosives (ATF) data indicates that 9mm Luger firearms were the most frequently recovered caliber in Oklahoma in 2023, accounting for 2,256 of 5,562 recovered firearms [33]. Glock barrels traditionally have polygonal rifling, however the Glock Gen5 models incorporate an improved marking barrel known as the Glock Marksman Barrel (GMB) [4, 34]. Compared to previous Glock barrels, the GMB includes micro lands along the edges of each polygonally rifled section, known as rails and enhance rifling characteristics and potentially improving shooting precision [17, 18]. Additionally, the enhanced rifling features within the GMB produce sufficient marks on bullets, which allowed for identifications to be made between bullets and barrels [18]. Research on these newer barrels is limited, but some studies suggest that identifications may not be possible after 500 rounds of solid copper projectiles, with significant changes in characteristics observed [31]. The firearm for this study was handled and stored with respect to the University of Central Oklahoma’s Policy on Firearms for Classroom and Field Instruction.

2.2 Ammunition Types and Bullets

For this study, two ammunition types were selected: Federal American Eagle 9mm Luger 124-grain FMJ and Federal Syntech Range 9mm Luger 124-grain TSJ. The selections were based on their round-nose design, which ensures similar interaction with the firearm’s barrel, and their identical bullet weight, eliminating weight as a variable. Prior to firing, all bullets were engraved with their shot number to ensure they stayed in the correct order. The engravings with the shot number were located on the ogive of each bullet since the curved

nose does not make contact with the barrel during the firing process. When loading the engraved bullets into a magazine, it was ensured that the engraving was facing up. This was done to make phasing the bullets during comparison easier since LEA 1 would ideally be in the same orientation for all shots. The bullets were collected and stored consecutively to ensure the bullets would be examined in firing order.

2.3 Bullet Collection, Storage and Cleaning

There are multiple bullet recovery methods on the market, which include water recovery tanks, and fiber-based traps or rubber-based traps. The most common of the recovery methods are the water recover tanks [4].

Water-tank recovery systems are highly favored in forensic laboratories because they are the least abrasive method available, ensuring the optimal preservation of microscopic individual characteristics on fired ammunition [35]. However, major problems faced with water recovery are portability, weight, and the initial cost of a water tank being upwards of \$50,000. Fiber-based traps are an alternative which have been regularly used. Cotton-based traps are typically much less expensive than water based traps and tend to be less destructive to the shape of the bullet, however can be more abrasive to the individual characteristics than water [4]. However, cotton does require special precautions be taken to prevent the cotton from igniting [35]. Kevlar is an additional type of fiber that is also used for these types of traps. However, Kevlar fibers may not be favored since they can cause damage on the fired bullet from impact which could hinder the identification process [4]. Thus, rubber-based traps were ultimately chosen for the study.

The portable pistol bullet trap by Super Target Systems was used for bullet recovery. This portable bullet trap is made out of ballistic steel, and was filled with ballistic rubber mulch to catch the bullets and keep them intact [31, 36]. The bullet trap comes equipped with a “self-healing ballistic rubber” front panel which is designed to keep dust inside the trap and slow down bullets after impact [37]. The ballistic rubber front panel is approximately one inch thick and very dense. Some concern was expressed when observing the front panel of the bullet trap due to the thickness and density. It was speculated that firing bullets through this substrate could cause damage to the LEAs of a fired bullet. Thus, to prevent any potential damage to the test fires, a 6 inch by 6 inch section of the front panel was removed. This section of the trap was then covered with cardboard to prevent the rubber mulch from falling out of the trap.

For the control barrel, nine cartridges were loaded into the magazine and fired down range. An engraved FMJ cartridge for collection was loaded into a separate magazine and was fired into the ballistic rubber trap for collection. Shots one through 10 were collected followed by every 10th shot leading up to 490. Since shots one through 10 were collected, for consistency shots 491-500 were also collected. After which, the barrel was then cleaned with a wire brush, cotton patches, and gun oil. After cleaning the barrel, an additional 30 shots were fired and every 10th bullet was collected. Of the 530 total shots fired, 71 FMJ bullets were collected for analysis.

For the experimental barrel, eight cartridges were loaded into the magazine and fired down range. Following this, an engraved TSJ and FMJ cartridge were loaded into separate magazines and fired into the ballistic rubber trap for collection. The collected bullets were fired one at a time into the bullet trap and placed into individually labelled coin envelopes. Shots one through three were collected followed by every ninth fired bullet which were TSJ and every 10th bullet fired which were FMJ. This process was repeated until shot 500, after which the barrel was cleaned following the same process as the control barrel. Following the cleaning process, an additional 30 shots were fired. Since shots one through three were collected shots 501-503 were also collected for consistency. Every ninth bullet fired being TSJ and every 10th bullet fired being FMJ were also collected. Of the 530 shots fired, 59 FMJ bullets and 53 TSJ bullets were collected for analysis. The processes followed for both the control and experimental barrels, ensured the collected bullets were stored in the proper order in case any engravings had become damaged during the firing process.

2.4 Bullet Scanning

Conclusions derived using light comparison microscopy and pattern matching methods are considered subjective. The Cadre Forensics TopMatch-3D desktop system, which applies an objective and quantitative algorithm-based approach to forensic examinations, was used for this study shown in Figure [2.1](#), in an attempt to remove subjectivity based source determinations. The bullets were scanned in pairs of two and automatically rotated to scan each of the areas of interest containing unique individual characteristics around the bullets shown in Figure [2.2](#). To remove any debris from the fired bullets, they were cleaned with alcohol and cotton swabs, the bullets were then rolled in poster putty to remove any remaining debris following standard practice.



Figure 2.1: Cadre Forensics TopMatch-3D High Capacity Scanner

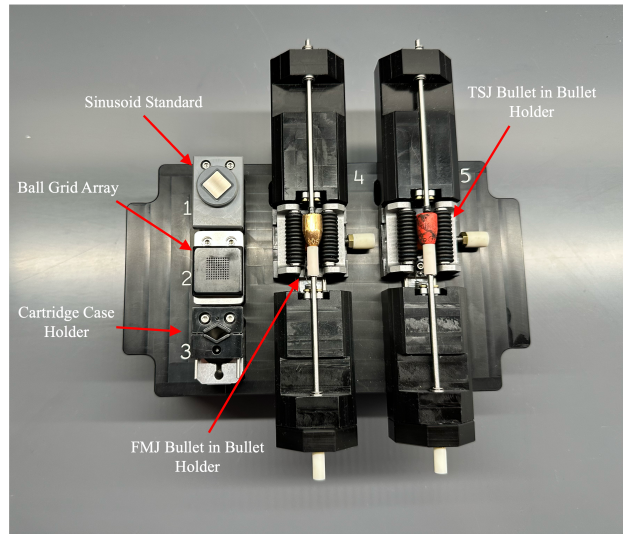


Figure 2.2: Cadre Forensics TopMatch-3D Bullet Tray. Cadre Forensics' new bullet tray features three numerically labelled cartridge case holder slots as well as two numerically labelled bullet holder slots. The cartridge case holders are removeable, so examiners can replace them with the sinusoid standard and (shown in holder 1) and the Ball Grid Array (shown in holder 2). The bullet holders are adjustable to fit various bullet sizes; such as a 9mm Luger FMJ bullet (shown in holder 4) and a 9mm TSJ bullet (shown in holder 5).

As previously mentioned, examiners typically use LEAs for forensic comparison due to their inclusion of striations and are less likely to possess subclass characteristics as GEAs [8-12]. Therefore, only the LEAs on the bullets were scanned. The GMBs being used for the study have six LEAs, which required six scans per bullet. With 130 bullet scans there

were 780 individual LEA scans. However, a total of 11 shots from the experimental barrel and 21 shots from the control barrel were excluded due to damage see Table 2.1. Figure 2.3 shows damage to the base, nose, or both on these bullets, disabling the bullets from rotating in the bullet holder leading to incomplete or impossible bullet scans. Ultimately, a total of 99 FMJ bullets (50 Control bullets and 48 Experimental bullets) were able to be scanned for a total of 594 individual LEA scans.



Figure 2.3: Example of damaged bullets

Table 2.1: Bullets excluded from data collection due to damage

Bullets Excluded from Control		Bullets Excluded from Experimental
B007		B010
B008		B040
B020		B170
B040		B200
B050		B230
B090		B270
B100		B280
B110		B310
B170		B440
B210		B502
B220		B510
B230		
B240		
B250		
B270		
B310		
B380		
B410		
B411		
B460		
B495		
Percent of Data Lost		Percent of Data Lost
29.58%		18.64%

2.5 Bullet Comparison

The TopMatch-3D system allows users to mask specific areas of interest, which the algorithm then compares against other scans shown in Figure 2.4. The bullets were analyzed using Cadre Forensics implementation of the Congruent Matching Profile Segments (CMPS) method, developed by the National Institute of Standards and Technology (NIST). The CMPS method segments masked areas and compares them using two criteria: (1) segments must demonstrate consistent similarities in striation depth and spatial patterns, even when segment size changes, and (2) segments must maintain their relative positions in the same order on both bullets [38]. If both conditions are met, the algorithm confirms the identification and proceeds with the remaining segments. Visual examinations were also conducted using Cadre’s Virtual Comparison Microscopy (VCM) software to verify the results produced by the CMPS method. The VCM software allows for traditional side-by-side view of images.

Additionally, users can also adjust the virtual light position, as well as manipulate the zoom and rotation [39].

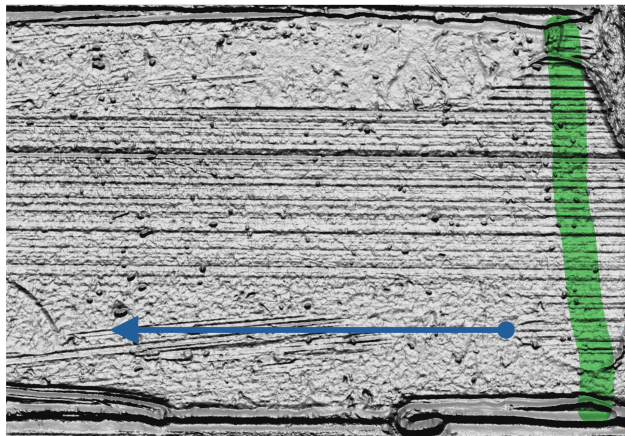


Figure 2.4: Depiction of scanned and masked LEA

2.6 Data Analysis

The Cadre Forensics CMPS algorithm produces similarity scores which are used to compare fired bullets to one another within the Cadre software. These similarity scores were used to test the data as a time series. Time series tests are applied to datasets collected at consistent intervals, where variations could arise [40]. The data for this study will be analyzed using the Kwiatkowski-Phillips-Schmidt-Shin (KPSS) time series test. Since the bullets for the study were collected in an evenly spaced interval they would fall under the parameters of a time series test. The firing of a bullet may affect the quality or quantity of individual characteristics in the LEAs, which would affect the similarity scores for future bullets. For example, bullets fired and collected later in the sequence could have less detailed individual characteristics and therefore lower similarity scores than bullets fired earlier in the sequence.

The KPSS time series test was selected due to its null hypothesis assuming the data is stationary, which indicates no change in the data or no significant barrel wear [41]. In the case of this study, the null hypothesis would be that the characteristics of the barrels do not change over time. The alternative hypothesis of the KPSS test, which would require a rejection of the null hypothesis, is that there is a change or trend in the data indicating non-stationarity. For this study, the alternative hypothesis would be that there is a change in the characteristics of the barrels. In a stationary time series, statistical properties like the

mean or standard deviation, do not vary over time [41]. However, in a nonstationary time series, statistical properties do vary over time.

The KPSS test rejects or accepts the null hypothesis based on the p-value. The p-value represents the probability of obtaining a test statistic, while assuming the null hypothesis is true [42]. Calculated p-values can range from 0 to 1, a p-value is considered significant if it falls under a defined significance threshold. A significance level of 0.05 corresponds to a 95% confidence interval and serves as the standard threshold in statistical testing [43]. Thus, the significance threshold for this study was set to 0.05. A p-value greater than 0.05 would indicate non-significance and therefore fail to reject the null hypothesis meaning that the data is stationary meaning no significant barrel wear occurred during the duration of the study. However, a p-value less than 0.05 would indicate significance and therefore reject the null hypothesis and accept the alternative, which means that the data is non-stationary meaning significant barrel wear occurred during the duration of the study.

3. Results and Discussion

3.1 Visual Examinations

Before the bullets were compared using algorithm scores and statistical analysis, visual comparisons were conducted to evaluate the condition of the LEAs, to track any changes that occurred throughout the study. Bullets 001, 100, 200, 300, 400, 500, and 530 from the control and experimental groups respectively were selected for the visual analysis. After bullet 500 each of the barrels were cleaned using firearm cleaning solvent and oil before an additional 30 shots were fired.

Figures [3.1](#) and [3.2](#) show all six LEAs on the bullet 001 through bullet 530 for both the control and experimental groups. In the figure, each column corresponds to a bullet and each row corresponds to a specific LEA. For example, the leftmost column shows all six LEAs for bullet 001, meanwhile the remaining images on the top row compare a corresponding LEA for the additional bullets. The LEAs in the photos were determined to be in best alignment which was aided with the use of the TopMatch algorithm.

3.1.1 Control Barrel

For the control group all six LEAs on bullet 001 have very defined striations. After 530 shots, while some features have become muted through wear it does appear that additional characteristics have developed. For example, LEA 5 B200 compared to B530 there are some additional characteristics on bullet 530 that have become prevalent throughout the firing process when compared to bullet 200. Additionally, some LEAs appear to have worn at different rates, specifically LEAs four and six visually show more signs of degradation. The striations on most LEAs shown in Figure [3.1](#) begin to show wear around bullet 200 with more notable changes appearing at bullet 500. Although wear is present in some regions, it is possible to confirm the algorithm's LEA alignment through pattern matching. This agreement was used to determine the correct order for the LEAs, by comparing the five

remaining LEAs in sequence and more striations were found to be in agreement. Manual comparison of bullet 001 and bullet 500 using VCM resulted in an identification. Regardless of assistance from the algorithm's alignment, an identification was still possible because of the quality of the striations. Due to FMJ ammunition having a copper jacketing it produces metal on metal contact with the barrel, and would produce more heat due to friction from traveling through the barrel. It was anticipated that the control barrel would sustain more barrel wear, or a degradation of characteristics, as a result of the increased heat and friction. However, as the visual results indicate this was not the case.

It is important to note again that some bullets sustained damage during the firing process which prevented them from rotating within the bullet tray. For the inclusive list of all damaged bullets see Table [2.3](#). These bullets had to be left out of the initial data analysis. Some measures were tested to remedy these damaged bullets, however bullets like C1-B100 yielded a partial scan as well as E1-B200 being too damaged to scan at all.

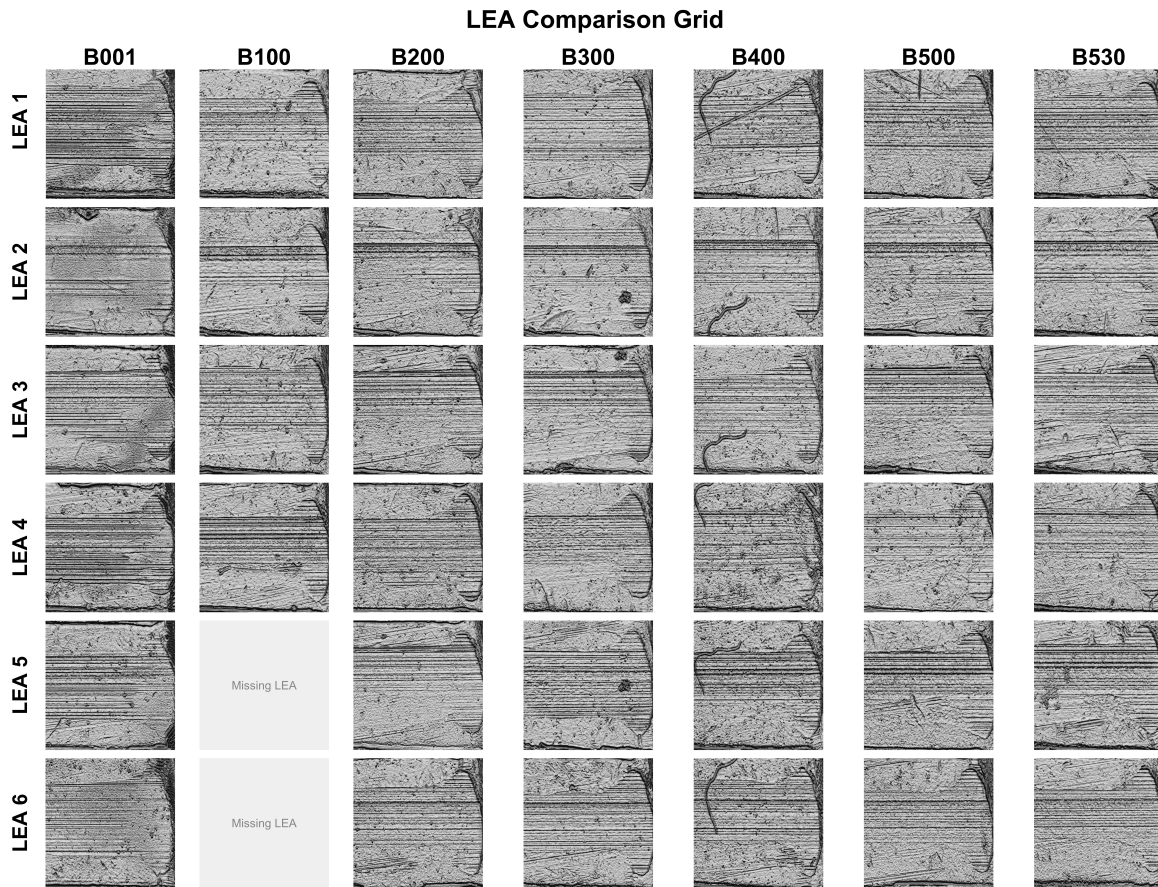


Figure 3.1: LEA Comparison Grid for the Control Group

3.1.2 Experimental Barrel

For the experimental barrel all six LEAs on bullet 001 also have very well defined striations. After the 530 shots, features show signs of significant wear and most striations have begun disappearing or have disappeared. The LEAs do appear to have been wearing at slightly different rates, specifically LEA one appears to have worn at a slower rate when compared the rest of the LEAs in the Figure [3.2](#). LEAs two, three, and four seem to be showing signs of wear as early as bullets 100 and 210, more noticeable changes appear by bullet 300 for all LEAs. As for the remaining three LEAs, changes in striations became more pronounced around shot 300. While wear is apparent, it becomes increasingly difficult to confirm the algorithm's LEA alignment through pattern matching. As with the control, this agreement was used to determine the correct order for the LEAs, by comparing the five remaining LEAs in sequence and more striations were found to be in agreement. When the algorithm's alignment was removed, an identification could not be reached due to the lack of quality and quantity striations on bullet 530. Visual comparison of bullet 001 and bullet 530 using VCM would likely lead towards an elimination or inconclusive. The original hypothesis anticipated that TSJ rounds would lead to decreased barrel wear due to the claims Federal premium had made regarding the ammunitions polymer coating preventing metal on metal contact between the bullets and barrel. However, it appears the experimental barrel sustained more wear than the control barrel. This could possibly be a result of uniform pitting of the polymer compound which exposes the lead core causing lead fouling within the barrel. Additionally, the degradation of characteristics visualized in the figure could suggest the polymer coating used for TSJ ammunition is harder than the barrel materials. This warrants further study into the polymer coating and the relative hardness of the materials when compared to copper jacketing.

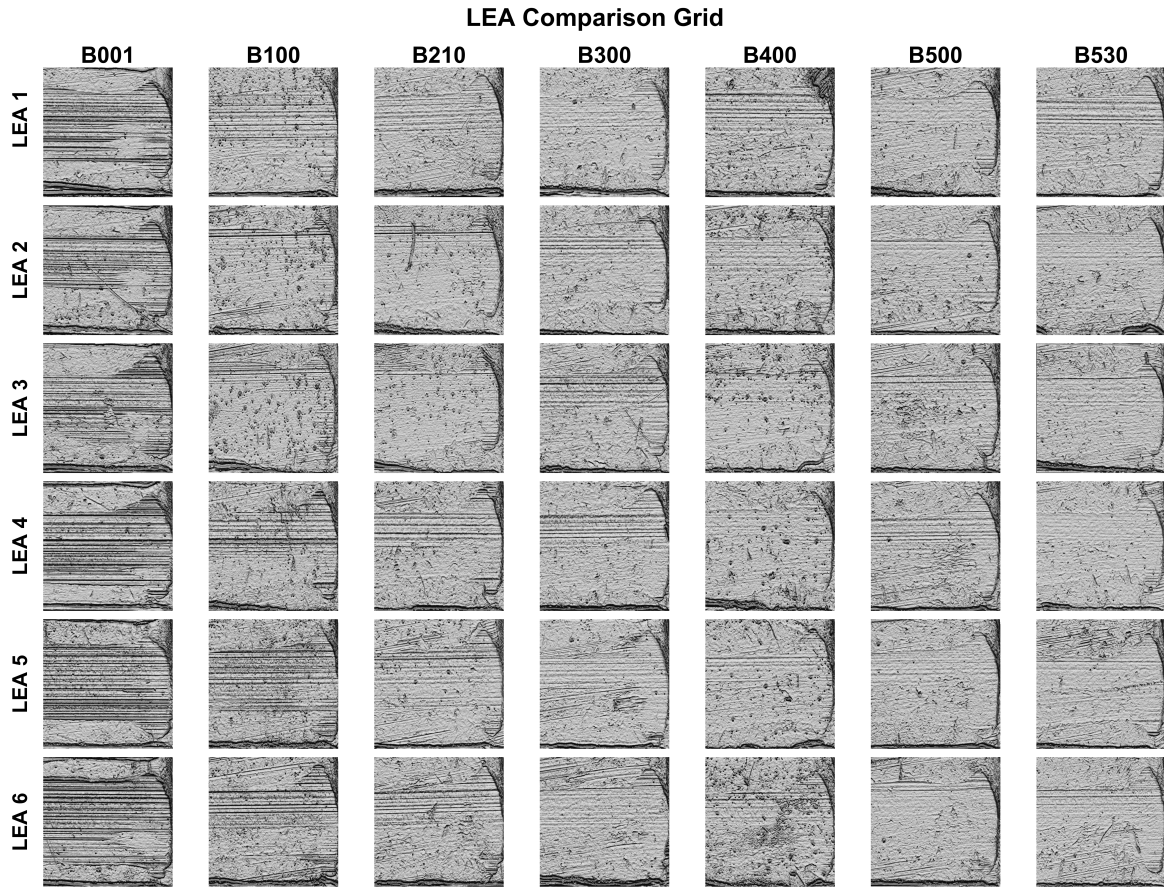


Figure 3.2: LEA Comparison Grid of the Experimental Group

In Figure [3.3](#), C1-B530 and E1-B530 LEAs 1-6 were compared to visualize the toolmarks produced by each barrel at the end of the study. Visually, bullet 530 from the control barrel retained a higher quality and quantity of striations compared to bullet 530 from the experimental barrel. While striations are present within the LEAs of E1-B530, they are of noticeably lesser quality than those found on C1-B530. These results indicate that TSJ ammunition could lead to increased barrel wear when compared to FMJ ammunition. As mentioned earlier, the increased barrel wear could be a result of the uniform pitting of the polymer potentially exposing the barrel to lead. Alternatively, the increased barrel wear could also be attributed to the hardness of the polymer coating.

Control vs. Experimental (Bullet B530)

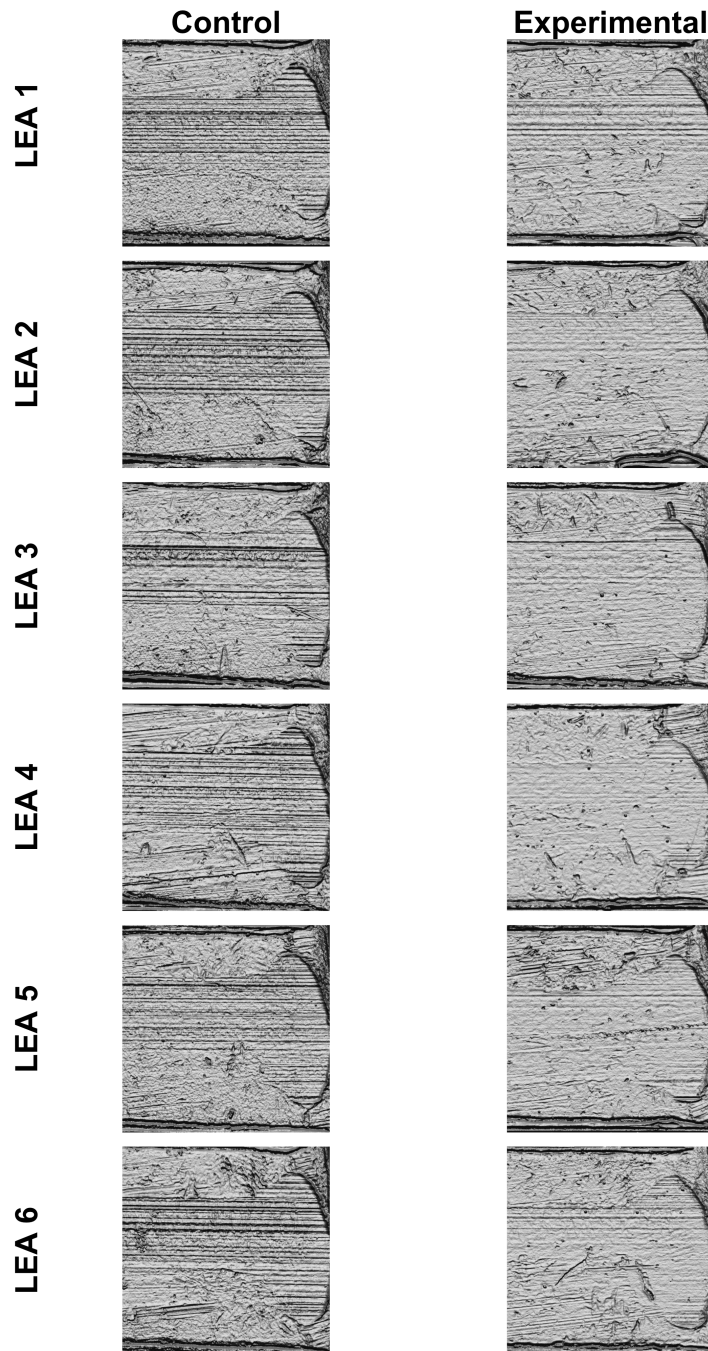


Figure 3.3: Control and Experimental B530 LEA Comparisons

3.2 Algorithm Data

The algorithm data for this study was derived from the Cadre Forensic CMPS algorithm which produces similarity scores. These comparison scores are used to inter-compare fired bullets between one another within the Cadre software. Similarly with the visual comparisons, bullet 001 was compared to bullets 100, 200, 300, 400, 500, and 530 respectively for the control barrel. For the experimental barrel, bullet 001 was compared to bullets 100, 210, 300, 400, 500 and 530 respectively.

3.2.1 Control Barrel

As Figure 3.1 depicted the development of additional characteristics in later shots. The CMPS similarity scores for the comparisons also portray that. Due to damage sustained during the firing process, the scan for B100 was incomplete and missing two LEAs. Because the Cadre software cannot intercompare bullets with a mismatched number of LEAs, the comparison between B001 and B100 returned a score of N/A. However, from the other CMPS scores listed in Table 3.1, there is a slight improvement of the characteristics since the CMPS scores experience a slow increase.

Table 3.1: Control Barrel Similarity Scores

Comparison	Overall Similarity Score
B001 vs B100	N/A
B001 vs B200	4.3333
B001 vs B300	4.8333
B001 vs B400	4.5000
B001 vs B500	5.5000
B001 vs B530	4.8333

This is further represented by Figure 3.4. As previously mentioned, the data for this study was analyzed as a time series. Time series test can be applied to data that has been collected at evenly spaced intervals and could contain variations due to the interval collections [40]. Since the bullets for the study were collected in an evenly spaced interval they would fall under the parameters of a time series test. It is important to note that bullets 002-009 and 491-499 from the control barrel were collected to profile the individual characteristics at the beginning and end of the study. Although these bullets were collected and scanned, they were not included in the statistical analysis of the data set as using them would violate the evenly spaced requirement of a time series.

In this time series plot all measured CMPS scores are represented by a red point and interpolated CMPS scores are represented by a green point. It is important to note that all interpolated points were reserved for data points where no bullet scan could be taken due to the bullet being damaged. In these cases, the CMPS score from the previous bullet was inserted in place of the missing point. For example, C1-B040 was unable to be scanned due to damage, thus no CMPS score was available. To maintain the trend line, the score from C1-B030 was replicated for an interpolation of what C1-B040 should have represented. This process was then replicated for all missing CMPS scores within the time series. The resulting Figure 3.4 visualizes the barrel wear trend for the control barrel over the course of the 530 shots. The figure also features a trendline to aid in visualization of the overall trend which the data follows. As shown by the trendline, it becomes apparent that the data remains stable and has a slight upward trend.

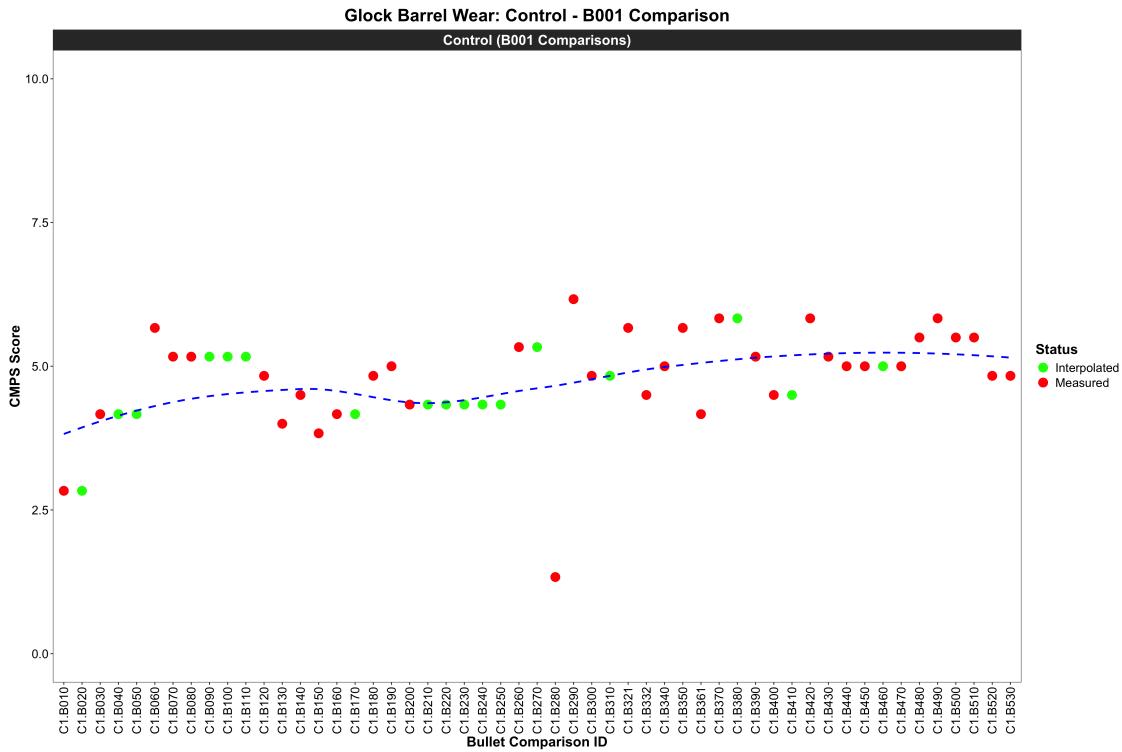


Figure 3.4: Time Series Analysis Plot of the Control Barrel

3.2.2 Experimental Barrel

As Figure 3.2 depicted visual degradation of striations, the CMPS similarity for the comparisons also portray that. The scores depicted in Table 3.2, start off relatively high with

B001 vs B100 recording a 6.5000 CMPS score. However, after B001 vs B210 the scores seem to drop by nearly half and remain consistent around the 3.5000 range.

Table 3.2: Experimental Barrel Similarity Scores

Comparison	Overall Similarity Score
B001 vs B100	6.5000
B001 vs B210	3.5000
B001 vs B300	3.6667
B001 vs B400	3.0000
B001 vs B500	3.3333
B001 vs B530	3.5000

These findings are further represented by Figure 3.5. As previously mentioned, the data for this study was analyzed as a time series. Time series tests can be applied to data that has been collected at evenly spaced intervals and could contain variations due to the interval collections [40]. Since the bullets for the study were collected in an evenly spaced interval they fall under the parameters of a time series test. It is important to note that bullets 002, 003, 502, and 503 from the experimental barrel were collected to profile the individual characteristics at the beginning and end of the study. Although these bullets were collected and scanned, they were not included in the statistical analysis of the data set as using them would violate the evenly spaced requirement of a time series.

In this time series plot all measured CMPS score are represented by a red point and all interpolated CMPS scores are represented by a green point. It is important to note that all interpolated points were reserved for data points where no bullet scan could be taken due to the bullet being damaged. In these cases, the CMPS score from the previous bullet was inserted in place of the missing point. For example, E1-B040 was unable to be scanned due to damage. Thus, since no CMPS score would be available, to follow the trend line of the dataset the score from E1-B030 was replicated for an interpolation of what E1-B040 should have represented. This process was then replicated for all missing CMPS scores within the time series. The resulting figure visualizes the barrel wear trend for the control barrel over the course of the 530 shots. The figure also features a trendline like the previous image to aid in visualization of the overall trend which the data follows. As shown by this trend line, it is apparent that the data does have a declining trend before leveling off towards the end of the shot range.

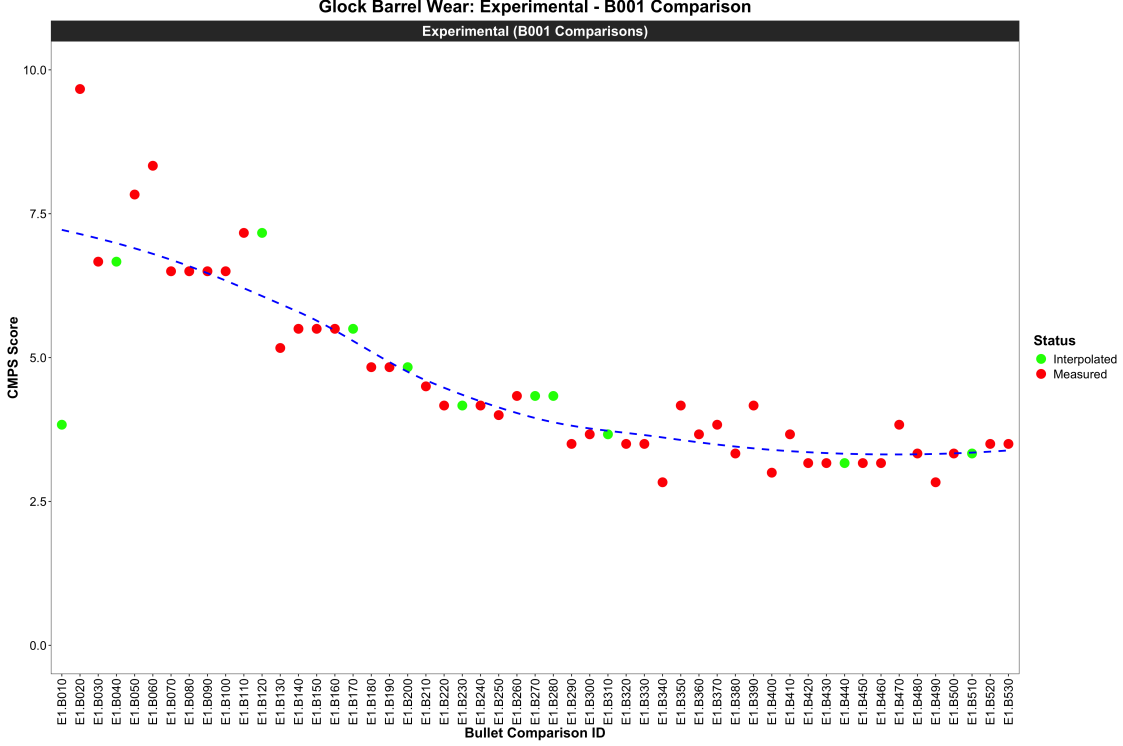


Figure 3.5: Time Series Analysis Plot of the Experimental Barrel

3.3 Statistical Analysis

As mentioned in Section 2.6, The KPSS time series test was selected due to its null hypothesis assuming the data is stationary, which would indicate no change in the data or no significant barrel wear. The KPSS test fails to reject or rejects the null hypothesis based on the p-value. The p-value represents the probability of obtaining a test statistic, while assuming the null hypothesis is true. Calculated p-values can range from 0 to 1, where a significant p-value is fall lower than 0.05 in the case of this study. For this study, all p-values were calculated using the `kpss.test` function within the `tseries` R package [44].

3.3.1 Control Barrel

The calculated p-value for the Control Barrel was 0.021, which falls below the significance threshold of 0.05. Therefore, the null hypothesis would be rejected and alternative would be accepted. Thus, the data observed in Table 3.1 and Figure 3.4 is non-stationary and significant. Furthermore, the slight upward trend seen in the time series plot suggests the control barrel developed additional characteristics throughout the study as a result of normal

barrel wear. This is supported by both the gradual increase in CMPS scores with Table 3.1 and the visual development of new characteristics in shots fired later in the sequence seen in Figure 3.1. The results derived from the statistical analysis of the control barrel supported the results seen visually. The control barrel did experience a change through barrel wear which resulted in the addition of characteristics.

3.3.2 Experimental Barrel

The calculated p-value for the Experimental Barrel was 0.01, which falls below the significance threshold of 0.05. Therefore, the null hypothesis would be rejected and alternative would be accepted. Therefore, the data observed in Table 3.2 and Figure 3.5 would also be non-stationary and significant. While the experimental data is also significant, the dramatic downward trend seen in the time series analysis plot indicates that the experimental barrels characteristics have worn or degraded throughout the study as a result of barrel wear. Which would be supported by both the gradual decrease in CMPS scores seen in Table 3.2 and the visual degradation of characteristics in shots seen in Figure 3.2. The results gathered from statistical analysis of the experimental barrel supported the results seen visually. The experimental barrel also experienced a change through barrel wear which resulted in the degradation of characteristics.

3.4 Limitations and Future Considerations

One limitation of this study would be the bullet collection method used. While the Super Target Systems portable bullet trap managed to keep most bullets in pristine condition, some projectiles sustained damage during the firing process, leading to additional difficulties during scanning. A water recovery tank or fiber-based trap might be worth exploring, alternatively filling the bullet trap with additional materials may reduce the likelihood of damaging the bullets as well.

Secondly, if a bullet had slight damage on the base, nose or ogive it would hinder rotation in the bullet tray, resulting in incomplete bullet scans. In an attempt to salvage these damaged bullets, double casts were made to experiment with adding material on the nose, and ogive to aid in rotation of the bullet in the bullet holder shown in Figures 3.6 and 3.7 [45]. Some attempts were also made to cut portions of the casts off to aid in rotation of the bullet. These attempts were moderately successful and led to some additional acquired scans which were included in the final analysis. Another remedy that was utilized was inserting

the damaged bullets back into cartridge cases which was also moderately successful. Figure 3.8 depicts the damaged bullets being inserted into fired cartridge cases. It was speculated that the reflection of light from the cartridge cases was interfering with the Cadre TopMatch System from recognizing the first LEA on the bullets. To address this issue, cartridge cases were wrapped in various colors of tape. However each workaround for the damaged bullets introduced its own complications with the Cadre TopMatch System.

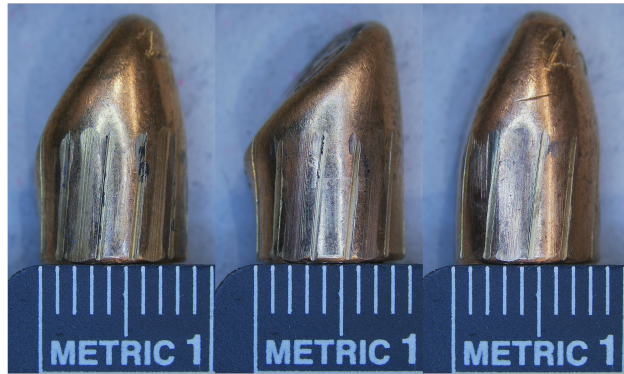


Figure 3.6: FMJ Bullets Selected for Double Casts

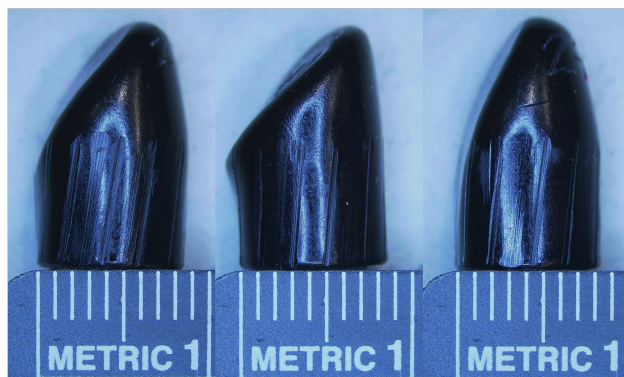


Figure 3.7: Double Cast Replicas of the FMJ Bullets

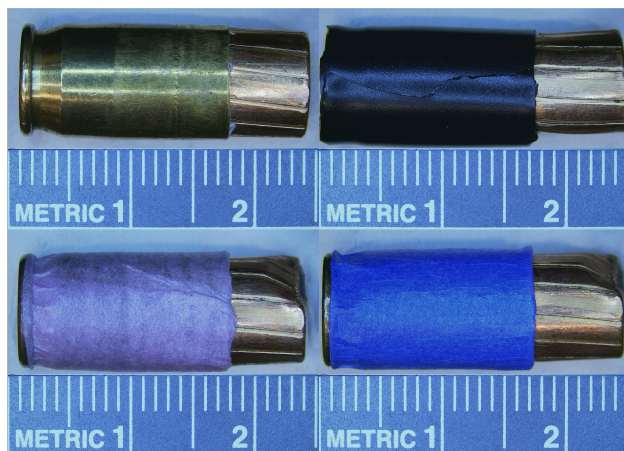


Figure 3.8: Damaged FMJ Bullets Inserted into Fired Cartridge Cases

Lastly, the final limitation of this study would be based on the study's design. The sample size of the study included only 500 bullets while comparable research has included 1,000 or more bullets. Since the sample size was smaller, the results of this study may not be as generalized as those with larger sample sizes. Furthermore, the sample size in the study was limited by only incorporating one control and experimental barrel. As a result, it cannot be determined whether the barrel wear trends observed are representative of this barrel or merely anomaly. In addition, the results of this study may be limited since the barrel used was a Glock Marksman Barrel (GMB). The GMB is only found in Glock Gen 5 which was introduced in 2017 and newer Glock firearms. Thus, not only could the results be limited to Glock firearms but could be limited to only newer Glocks with GMBs. Additional research needs to be conducted to evaluate how TSJ ammunition affects older Glock models in addition to other firearm brands.

4. Conclusion and Future Research

Results of this study have shown that Federal Premium's TSJ ammunition, may cause degradation of individual characteristics within the barrel over the course of successive firing. The lack of individual characteristics retained by the polymer surface make these bullets counterproductive to forensic investigations. Furthermore, the reduced metal-on-metal contact intended to extend barrel life compared to FMJ ammunition may actually be detrimental to the life of the barrel characteristics. The barrel wear trends witnessed in this study could indicate that the polymer coating used for TSJ ammunition is harder than barrel materials, causing it to degrade barrel characteristics faster than anticipated. The relationship between the observed barrel wear and projectile accuracy was not evaluated in this study and is unknown.

In contrast, the control barrel depicted a development of individual characteristics, as a result of successive fire, when compared to the experimental barrel. Previous research utilizing FMJ bullets or solid copper bullets, which produce metal on metal contact within the barrel have shown that identifications may be possible after successive fire. While individual characteristics within the barrel do degrade with successive fire, sufficient agreement between the LEAs is still generally present.

Finally, it was anticipated that the findings to support the hypothesis that TSJ ammunition does lead to decreased barrel wear due to the polymer coating. However, with this study it has been shown that TSJ ammunition may cause increased barrel wear when compared to traditional FMJ ammunition. The results of this study are significant to the firearms discipline because it explores the impact of different ammunition on a commonly used firearm. Furthermore, this study explores how toolmarks evolve with different ammunition types over successive fire. Examiners should approach barrels that may have fired TSJ ammunition with caution since increased barrel wear could lead to difficulty in forensic comparisons.

Ongoing research is examining additional polymer coated ammunition to see if wear patterns remain consistent despite possible varying polymer composition. Future research, could examine other companies that produce ammunition similar to Federal Premiums' TSJ.

Establishing wear patterns and assessing the potential for forensic identification of these alternative ammunition types as well. Additionally, research into wear patterns and forensic identifiability of homemade bullet coatings could also be worthwhile. Companies like Hi-Tek, have put polymer coated ammunition into the hands of home loaders which could have its own forensic implications. Lastly, additional research could examine the various ways to 3D scan damaged bullets utilizing the Cadre TopMatch System.

5. References

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