The Origin of Individual Characteristics and the Persistence of Reaming Marks After Button Rifling

By: Brandon A. Best and Elizabeth A. Gardner, University of Alabama at Birmingham, Birmingham AL

Keywords: button rifling, consecutive barrels, crowning, individual characteristics, reaming

ABSTRACT

Individual characteristics are imparted on fired bullets by microscopic imperfections or burrs in the barrel of the firearm, left during the various machining operations used in its manufacture. These characteristics can also come from any changes that occur inside the barrel or muzzle through use or abuse. The depth, contour, and relative spatial orientation of the resulting striations left on the fired bullets are the subject of microscopic comparison to establish an association with, or elimination from a particular firearm. Individual characteristics can be created from the combination of a multitude of factors. The bores of ten barrels were cast after the reaming operation then again after button rifling. Comparisons of pre-rifling to post-rifling casts show the reaming marks survive the button rifling process. Three barrels were sent back to the manufacturer to have the crown recut a second time. Test fires from before the second crowning were compared to post-recrowning test fires. Comparisons of pre- to post-recrowning test fires indicate that the individual characteristics were altered to the point of being unidentifiable. This was found to be due to the use of a piloted crowning tool that abraded the lands at the muzzle end as it rode on top of the rifling. Finally, to establish which area of the barrel imparts the individual characteristics, the bore of one barrel was sanded at increments of one inch, from chamber to muzzle. After each section was sanded, the barrel was test fired and the bullets collected for comparison to a pre-sanding reference bullet. The bullet comparisons indicate that sanding the imperfections at the muzzle created the most drastic change in the markings on the bullets. Removing the reaming marks on the surface of the lands and the corresponding change in individual characteristics imparted to the bullet, indicates that pre-rifling processes, such as reaming, have the most impact on individual characteristics.

Introduction

Individual characteristics are microscopic marks imparted on the bullet from the firearm that are an unintended consequence of manufacturing. These marks are individual to the firearm and are used to link fired bullets and cartridge cases to the firearm that fired them. Individual characteristics on fired bullets and cartridge cases originate from the machining processes performed during the manufacturing of the firearm as well as from use, abuse, and wear over time. The uniqueness of individual characteristics from the manufacturing comes from a variety of factors, including chip formation, built-up edge, rake angle, and wear and tear, to name a few.

Pre-rifling operations can be subdivided into cutting, sanding, and burnishing. Cutting processes include gun drilling, reaming and cut rifling. These processes leave microscopic defects in the metal as a result of chip formation. The chips form ridges of metal that stand proud of the barrel surface in the form of a microscopic burr or defect. Conversely, sanding processes like honing and sand blasting remove metal abrasively, leaving unique furrows as the abrasive tool itself undergoes wear and abrasive particles fall off. Unlike cutting and sanding, burnishing applies great pressure to the metal to force metal from raised areas into low areas. This creates a mirror smooth surface. More than one pre-rifling process may be used. For instance, a reaming process may be used to achieve the final bore diameter of a barrel and be followed by burnishing to smooth out the microscopic reaming marks. The pre-rifling process is typically the last machining process to contact the land surface before rifling and is thought by some to be the primary source of individual marks transferred to a bullet upon firing **[1]**. These unique characteristics formed in the barrel are used to identify fired bullets to the barrel from which they were discharged **[2, 3, 4, 5, 6]**.

Crystalline Structure of Metal

Metals, especially alloys, are composed of a crystalline structure characterized by grains and grain boundaries. Metals are often melted to purify and form shapes in molds. As the metal cools and transitions from a liquid to a solid, the atoms of the metal will begin to aggregate and form crystals. Aggregation is initiated at multiple sites simultaneously. The crystalline structure differs by the type of metal, additives, coatings, and how the metal was formed, e. g, drop forged,

Date Received: December 05, 2022
Primary Review Completed: February 09, 2023
Secondary Review Completed: March 22, 2023

cold rolled, annealed, quenched, et cetera.

The crystals form in different orientations relative to one another to create grains. The shape of each grain is governed by its neighboring grains and the space it occupies. The resulting grain boundaries are unique **(Figure 1) [7]**. The metal atoms in the crystals are uniformly arranged over great distances; however, the grain boundaries are not uniform and produce narrow linear areas of disorder in the structure of the metal. The grain structure is random in shape, size, and orientation. The force of a blade being pushed into the metal causes the metal grains to separate, essentially fracturing the metal along the grain boundary. This means the sheared area leaves a microscopically rough surface that is random in structure.

Exposure to increased temperature below the melting point of the metal, such as in tempering, can lead to a phenomenon called "grain creep". The elevated temperature frees the grains to slide past one another, further changing the grain orientation. Finally, the way a metal is shaped during manufacturing can also affect the grain structure of the metal. For instance, cold working fractures the grains and makes the grain boundaries more irregular. Conversely, annealing makes the grain boundaries more regular and relieves stress on the metal. However, the boundaries are still not uniform.

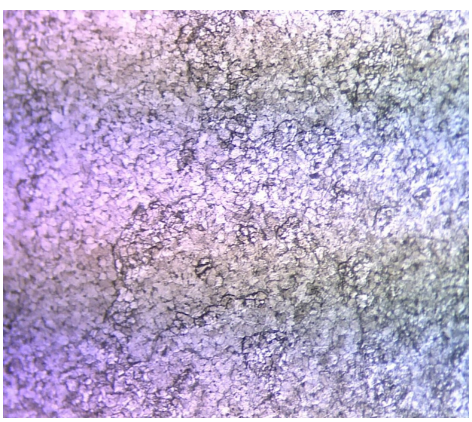

Figure 1: Grain boundaries and crystalline structure of 1018 mild steel at 60x total magnification. Etched in 10% Nitric Acid.

The density of the metal workpiece and its crystalline structure play a part in determining the rate and extent of chip formation due to the built-up edge, discussed below. If the metal is very dense or hard, like tungsten, then the crystalline structure is brittle, and the metal will fragment off the workpiece in small discontinuous chips. However, if the metal is soft, such as aluminum, then chips may come off in long ribbons as continuous chips. The built-up edge also depends on the speed, surface area of the blade, friction, and rake angle **[8, 9]**.

Chip Formation

Chip formation is a phenomenon seen in cutting processes and is the basis of the individual characteristics created during manufacturing, albeit not the only way to create individual characteristics. As the cutting tool contacts the metal workpiece, material begins to separate at the grain boundaries and move up the surface of the blade. Once the material riding up the blade reaches a point that it can no longer support itself and loses structural integrity it will break, and a chip is formed. At the point where a chip breaks off, a microscopic imperfection results on the surface of the workpiece. The chips can be continuous or discontinuous, depending on the cutting speed, surface friction, type of metal, feed rate, and rake angle **(Figure 2)**. Continuous chips are typically formed in low rake angle with low friction on soft metals. The chips can be extremely long and form a ribbon. Continuous chips can sometime mar the surface of the workpiece. This also contributes to individual characteristics. Discontinuous chips are short, choppy fragments. This type of chip is typically formed with higher rake angles, higher friction, and harder metals **[8, 9]**.

Built-up Edge

A phenomenon associated with chip formation is the built-up edge. As friction causes the blade to heat, metal from the workpiece will begin to weld itself to the tip of the cutting blade. This built-up edge then becomes the cutting surface and continues to grow in size until it breaks off at random intervals and moves under the cutting blade. The metal that breaks off leaves a ridge in the surface of the workpiece, contributing to the creation of individual characteristics **[8, 9]**.

Rake Angle

The rake angle is the angle at which the cutting blade meets the workpiece. The greater the angle, the higher the friction and vibration, called chatter, will occur. Chatter contributes to the

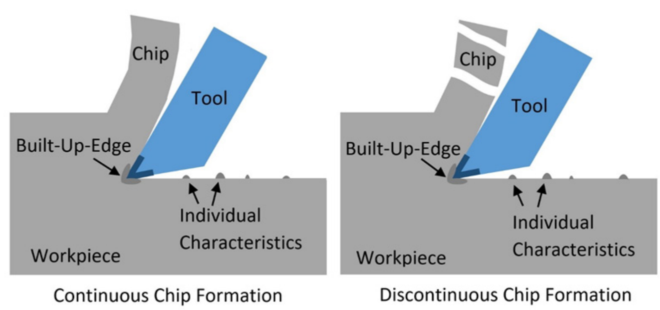

Figure 2: Continuous and Discontinuous chip formation with built-up-edge (BUE).

formation of individual characteristics as the blade bounces on the workpiece. The greatest friction and subsequent chatter occurs when the rake angle of the blade is perpendicular to the workpiece. If the rake angle is greater than parallel, but less than 90°, the blade will ride along the workpiece with less friction and less chatter. This results in a smoother workpiece, although metal will still build up and break off from the edge of the blade **[8, 9]**.

Other Factors

Another factor that leads to uniqueness is changes to the cutting tool over time as it wears. Microscopic imperfections and damage to the cutting tool can introduce new marks to the workpiece. Surface defects from machining processes, such as porting, gas ports, and crowning, may also create individual characteristics on fired bullets. This is especially true if the crowning tool is piloted and contacts the rifling at the muzzle. Finally, although each barrel will leave the factory with unique characteristics, additional individual characteristics may be added due to wear from normal use and abuse over time **[8, 9]**.

Reaming Tool

The reaming tool lasts for approximately 400 barrels **[16]**. Every bore is checked after reaming and once the inner diameter is out of tolerance, the reaming tool is replaced. The reamer itself is tapered with the center of the tool at the required 0.347-inch (8.81mm) diameter for a .38 caliber class barrel. As the reamer progresses through its life, the blade will begin to wear, change, and reduce in diameter. The reamer will also begin to show signs of wear and imperfections in the blade **(Figure 3)**. Due to the taper of the reamer, this means that as the reamer wears, more of the blade will contact the bore of the barrel. Eventually, enough of the reamer has been removed that the inner barrel diameter is out of tolerance.

Rifling Button

Each button can rifle thousands of barrels in its life span **[16]**. The grooves on the button makes the lands in the firearm. The button has large continuous striations within the grooves. The striations are formed by the grinding process used in the manufacture of the button **(Figure 4)**. The groove on the button is 0.020-inches (0.508mm) deep as opposed to the 0.004-inch (0.102mm) height of the lands in the barrel. The grooves on the button, which form the lands in the barrel, are deep enough that the land should never contact the bottom of the groove on the button and the characteristics from the button are never etched into the lands of the barrel **(Figure 5) [10]**.

The second stage lobe of the button is generally smooth, lacking stria, and does contact the land of the barrel; however, this stage only displaces 0.001-inches (0.025mm) of metal over the entire circumference of the bore, once the metal relaxes due

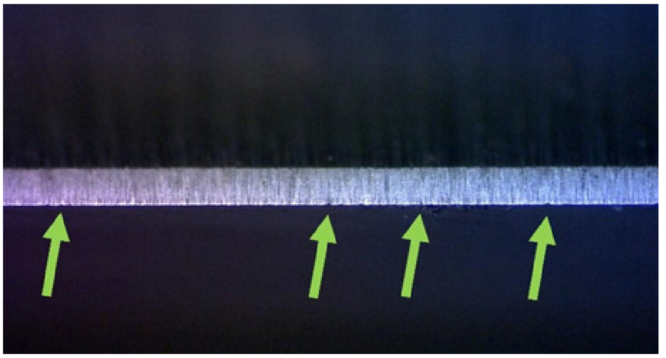

Figure 3: Reamer blade at 40x total magnification. Arrows indicate imperfections in the blade cutting surface from wear.

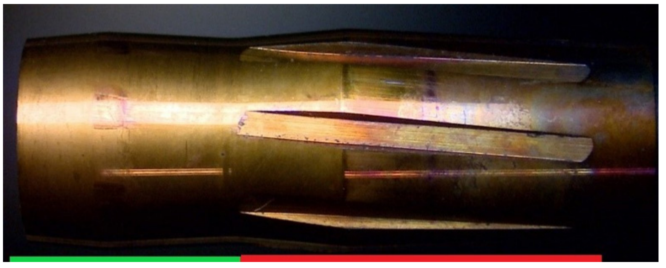

Figure 4: Two stage button used to consecutively rifle barrels 1-10. First stage lobe indicated in red. Second stage lobe indicated in green.

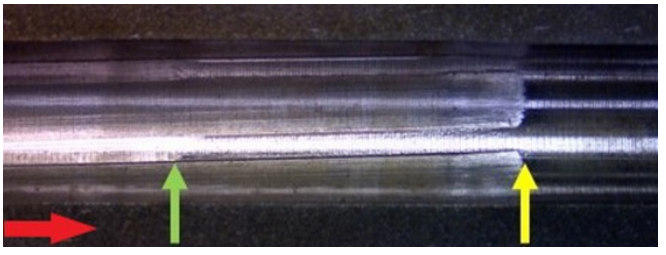

Figure 5: 223 Rem caliber barrel cutaway from Smith & Wesson where the button became stuck at 4x total magnification. Completed rifling that encountered the first and second stage lobes (Left), rifling of just the first stage lobe (Center), and unrifled reaming marks (Right). The green arrow indicates transition from second stage lobe to first stage lobe and the yellow arrow indicates the transition from first stage lobe to unrifled reaming marks. The red arrow indicates direction of button travel through the bore.

to elastic deformation. This increases diameter of the reamed .38 class barrels from 0.346-inches to 0.347-inches (8.79mm to 8.81mm) from land to land. The second lobe burnishes the lands, but the reaming marks can potentially survive. The first lobe of the button, which has the rifling ground into it, is 0.360-inches (9.14mm) in diameter and the second lobe of the button is 0.350-inches (8.89mm) in diameter. Therefore, the second stage lobe forces 0.004-inches (0.102mm) of the land surface back over the circumference of the barrel and then the metal relaxes 0.003-inches (0.076mm) down to a bore diameter of 0.347-inches (8.81mm) from land to land. As the button nears the end of its life, large defects may be found on the second stage lobe that can affect the surface finish of the land. A cast of a barrel affected by defects in the second stage lobe would reveal striations on the lands that run parallel to the barrel **(Figure 6)**.

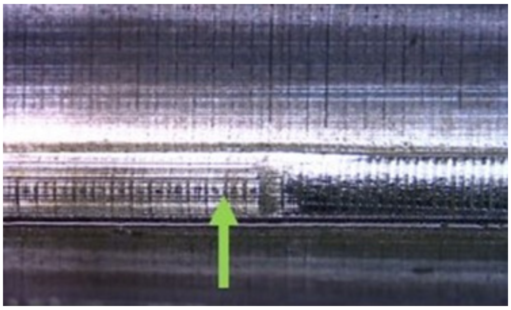

Figure 6: Land rifled with first and second stage lobes (Left) with a button at the end of its life with defects (Green arrow) that run parallel to the barrel as compared to the land only touched by the first stage lobe (Right) at 10x total magnification.

Bullet comparisons are primarily based on the stria left by the lands in the barrel, leaving land impressions on the bullet. The stria on the groove impressions may also be individual characteristics. This is because marks in the groove of the barrel come as a result of the reaming marks that survived button rifling. But care must be taken not to mistake subclass characteristics for individual characteristics. Any large defect on the button could potentially survive from one barrel to the next. Therefore, if an identification is to be made on groove impression marks alone, a cast of the barrel should be taken, and checked for the presence of gross continuous marks in groove impressions **[11]**.

Once bullets are fired and engraved with unique characteristics from the barrel, damage may be incurred as a result of striking a target. Damage to the bullet can result in foreshortening and partial or complete obliteration of the individual characteristics. This is common in casework and, as such, contributes to the difficulty of bullet comparisons. However, identification is still possible with damaged bullets, depending on what areas remain and to what extent the bullet is damaged [**11, 12]**.

Purpose

It has been asserted that the last manufacturing process to contact the bore of the barrel is responsible for imparting individual characteristics on fired bullets **[1]**. The last process to contact the bore of the ten barrels in this study was the button rifling process; however, as early as 1957, studies have been conducted that show reaming marks from the previous manufacturing process may survive and contribute to individual characteristics **[10].** The purpose of this study was to determine:

- If reaming marks could survive the forces of button rifling,

- If the reaming pre-rifling process is responsible for individual characteristics imparted on fired bullets, and

- What area of the barrel is of most importance for imparting individual characteristics on fired bullets.

The combination of reaming followed by button rifling was selected because it is a common barrel manufacturing process **[13].** The vast majority of manufacturers that use button rifling also use reaming as the pre-rifling process. This is because reaming can cut the barrel with tight inner diameter tolerances that extend the button tool life.

The survivability of reaming marks was determined by examination of the barrels before and after button rifling. Once the source of the individual marks was determined, experiments to determine the location of the marks that produce the striations on a fired bullet were conducted.

Murdock determined that crowning did not sufficiently alter the marks transferred to fired bullets to prevent an identification **[14]**. He did, however, opine that reaming marks in the barrel at the muzzle were the source of individual marks. To test this, three of the barrels underwent a second crowning process to determine if crowning affected the individual characteristics in the barrel. Finally, one barrel was subject to an incremented barrel sanding process to determine the position in the barrel where individual characteristics transferred onto fired bullets.

Methods and Materials

Smith & Wesson provided ten consecutively manufactured Thompson/Center Arms G2 Contender barrels for the purpose of this study. The barrels started as steel bar stock that was deep hole drilled to establish a rough bore. At this point, the barrels were engraved one through ten to maintain the order for subsequent processing. The barrels were then consecutively reamed in order, one through ten, to an inner diameter of 0.347-inches (8.81mm) using the same reaming tool. This inner diameter was necessary because the barrels were to be chambered in .357 Magnum. Barrels rifled for .38 caliber class barrels have a land-to-land diameter of 0.347-inches (8.81mm) **[15].** The four bladed reaming tool used was at the end of its production life.

Following the reaming process, the barrels were mailed to the laboratory for analysis. The bore of each barrel was examined using a borescope and photographs were taken. An AccuTrans™ cast was then taken of the full length of each barrel. A witness mark was engraved at 12 o'clock at the chamber end of each barrel and a marker was placed in the setting cast material to coincide with this witness mark for orientation.

After this mid-production analysis, the barrels were shipped back to Smith & Wesson for completion of the manufacturing process. The barrels were then button rifled using the same carbide button tool for all the barrels. The button tool used on these ten barrels was at the start of its life. The button was forced through each barrel with roughly 2,500 pounds of force **[16].** The chambers were then consecutively reamed, the muzzles consecutively crowned, heat treated, and finally shipped back to the laboratory in their finished state. Once back at the laboratory, the barrels were again cast and oriented to the witness mark. Before any further analysis, each barrel was fired 25 times using full metal jacketed PMC Bronze .38 Special caliber 132-grain ammunition as a break-in period.

Second Crowning

Three of the barrels, numbers 6, 8, and 9, were sent back to Smith & Wesson to be crowned a second time to determine if this would alter the individual characteristics. Five test fires were collected from each of the barrels before shipping them back to the factory. The recrowned barrels were then shipped back to the laboratory where five more test fires were collected from each of the three barrels. The pre-recrown test fires for each barrel were microscopically compared to the post-recrown test fires. AccuTrans™ casts were also taken after the second crowning procedure for comparison to original crown casts.

Sanding Method

Barrel #6 was selected to undergo sanding of the bore in increments of 1-inch (25.4mm) **[17]**. The barrels are a total length of 12-inches (304.8mm), 2-inches (50.8mm) of which are chamber and 10-inches (254mm) are rifling. The 10-inches (254mm) of rifling was sectioned off in ten 1-inch (25.4mm) increments. Starting at the chamber end working towards the muzzle, the lands were abraded using 220 grit sandpaper discs on a dowel rod. The sanding disc was approximately 0.75-inches (19.05mm) wide. Approximately fifteen to twenty passes were made at each 1-inch (25.4mm) increment position, making sure to cover the full diameter of the barrel at that position. Following sanding at the given position, two oil coated patches were passed through the barrel originating from the muzzle end so as to not contaminate other areas of the barrel with sandpaper particles. Using PMC Bronze 132 grain FMJ .38 Special ammunition (lot # 38G-1064), two bullets were fired down range to fully clear the barrel. Then, three test fires were fired into a water tank for collection. This process was repeated in 1-inch (25.4mm) increments for the remainder of the barrel. Collected test fires were then microscopically compared on the Leica FS C comparison microscope to determine if and to what extent the individual characteristics would change as the sanding progressed down the barrel.

Results and Discussion

Survival of Reaming Marks After Button Rifling

Examination of AccuTrans™ casts from the pre-rifling stage of each of the ten barrels showed clear concentric rings characteristic of reaming marks. The ten post-rifling casts exhibited similar rings. This indicates that the reaming marks survive the pressures of button rifling in both the land and groove **(Figure 7)**. There is a small upward shift of the reamer marks in the groove impressions. The shift is in the direction of travel of the button from chamber to muzzle **(Figure 8).** The concentric rings from the reaming process can be uniform in spacing. However, unique striations are etched onto the fired bullets as they move down the barrel perpendicular to the reaming marks. The bullet travels across the rings, some of which protrude further than others, and burrs on the rings scratch the bullet. These burrs are random in their creation, are individual and the direction of bullet travel across them negates any subclass influence.

A microscopic view of the bore of each barrel after reaming shows that some of the reaming marks are more prominent than others and that burrs protrude from the rings **(Figure 9)**. These burrs contact the bullet as it travels down the barrel and leave microscopic imperfections, or striae, on the bullet. Because the firearm is a fixed tool, subsequent firings will result in identical stria on each bullet, in the same relative

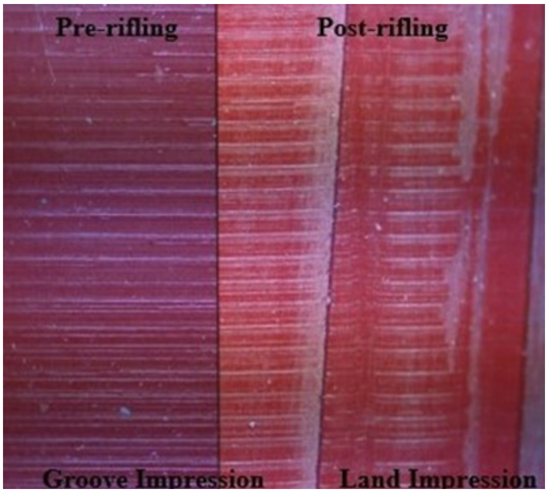

Figure 7: Barrel #6 cast comparison of reaming marks pre rifling (left) vs post rifling (right) in groove and land impressions further right at 20x total magnification 1 inch from muzzle (top).

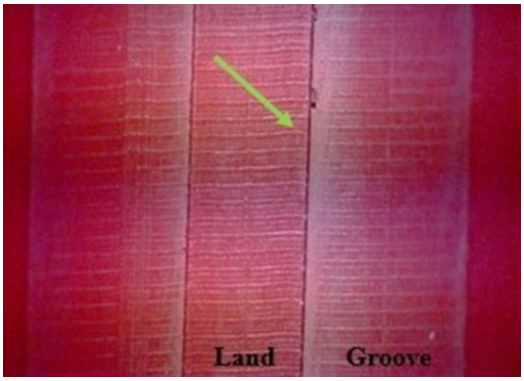

Figure 8: Cast of reaming marks in land and groove impression of barrel #6 at 10x total magnification, showing the reaming marks survive button rifling. Marks in the land impression are offset from marks in the groove impression due to button rifling, as indicated by the green arrow. The top is towards muzzle end.

positions. This leads to reproducible marks on bullets fired through the same barrel.

Second Crowning

The crowning process involves machining away the end of the barrel at the muzzle. This serves to make a more uniform profile, protect the ends of the rifling from damage, and to enhance accuracy. Smith & Wesson's crowning process for

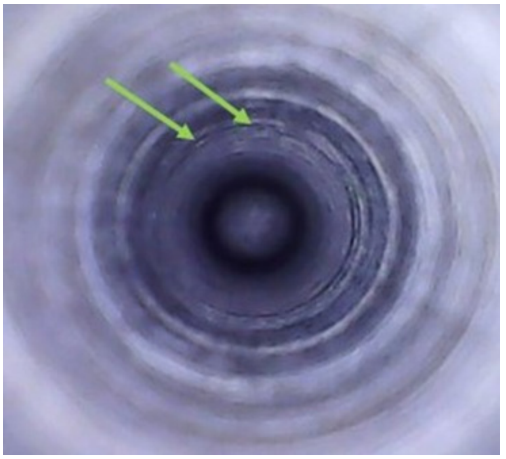

Figure 9: Concentric rings left in barrel #1 by the reaming process before rifling. Some burrs extend further out than others. Green arrows indicate burrs protruding from the rings.

this line of barrels involves a piloted tool that contacts the lands of the rifling at the muzzle end while it cuts a recess for the crown. The pilot of the crowning tool is 0.5-inches (12.7mm) long and the crowning process removes roughly 0.025-inches (0.635mm) from the muzzle **[16].** The intent of the crowning process for this line of barrels is a cleanup process rather than removal of large amounts of material. The crown on Contender barrels consists of a recessed table that contacts the rifling.

The 0.5-inch (12.7mm) pilot of the crowning tool removed a very small amount of material from the muzzle **(Figure 10)**. The reaming marks are still present at the muzzle end of barrels 6, 8, and 9 after recrown, even though the pilot of the crowning tool contacts the rifling. The reaming marks beyond 0.5-inches (12.7mm) from the muzzle are unchanged, but show signs of smoothing in the area 0.5-inches (12.7mm) from the muzzle by the pilot of the crowning tool riding on the lands during this process. This has led to changes in the individual characteristics of the reaming marks at the end of the barrel that were translated onto the bullets. Pre-recrowned and post-recrowned test fires were not identifiable as being fired from the same barrel, as the features at the crown had changed significantly, affecting the pattern of individual marks created. Piloted crowning tools can change the individual characteristics by removing some of the reaming marks even though traditional crowning tools that are not piloted have been proven to not alter the individual characteristics **[14].** It is important to note that most manufacturers' crowning operations do not use a piloted crowning tool; but rather lathe turning, CNC cutting, or other non-piloted methods.

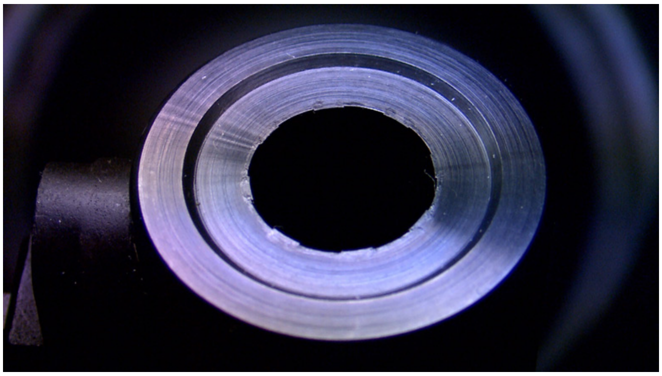

Figure 10: Crown of Barrel #6 before recrown at 4x.

Sanding

Bullets fired post and pre-sanding from 1-3-inches (25.4mm to 76.2mm) were still readily identifiable as being fired from the same barrel. There is a slight change in individual marks at the 4 and 5-inch (101.6mm and 127mm) marks. The gradual changes continue through 5-7-inches (127mm to 177.8mm). However, at 8-inches (203.2mm) the individual characteristics are changed to an extent that bullets can no longer be identified to bullets fired pre-sanding. At 10-inches (254mm) the individual characteristics have completely changed. The results of bullet comparisons at each interval of sanding are recorded in the following table **(Table 1)**.

The effect of the sanding was to create finer, more irregular surface contours. This resulted in less detail and an almost cloudy background in the land engraving **(Figure 11)**. A post-sanding cast of barrel #6 was taken. Microscopic examination of the cast revealed that most of the reaming marks on the lands had been removed by the sanding process **(Figure 12)**.

Microscopic comparisons of bullets fired pre- and post-sanding at the chamber end produced little change in individual characteristics and identification was easily accomplished. These comparisons were conducted by the author using a Leica FS C comparison microscope and the ground truth was known at the time of comparison. Sanding of the muzzle end, however, did significantly alter the individual characteristics imparted onto the bullet. Comparison of bullets fired pre- and post-muzzle sanding yielded significantly different individual characteristics, to the extent that an identification could not be made. Therefore, reaming marks at the muzzle end of the barrel are the last to contact the bullet and have the greatest effect on the individual characteristics. Individual characteristics imparted at the chamber end are overwritten as the bullet travels down the barrel. However, while gross characteristics closer to the chamber may still continue to be present on the fired bullet, the fine detail is created at the muzzle end.

Conclusions

Casts of barrels after button rifling show that the concentric rings from reaming survive the forces of button rifling in both the land and the groove. The individual characteristics transferred onto a fired bullet are from the reaming process and not from the button tool that creates the rifling.

Test fired bullets collected after the recrowning operation could not be identified to the bullets collected before the recrowning operation. This indicates that the pilot of the crowning tool altered the reaming marks at the muzzle end of the barrel and resulted in new individual characteristics imparted on the bullets. The small cleanup operation of crowning had a greater effect than all the marks left further up the barrel, indicating

Sanding Position (From Chamber to Muzzle)	Change in Striae	Comparison to Reference Result
1” (Chamber)	No Significant Change	Identification
2”	No Significant Change	Identification
3”	No Significant Change	Identification
4”	Slight Difference	Identification
5”	Slight Difference	Identification
6”	Moderate Difference	Identification
7”	Moderate Difference	Identification
8”	Substantial Difference	Inconclusive
9”	More Disagreement than Agreement	Inconclusive
10” (Muzzle)	Stark Difference; No Agreement	No Agreement

Table 1: Table of results from comparisons between the pre-sanding reference and bullets test fired after each interval of sanding.

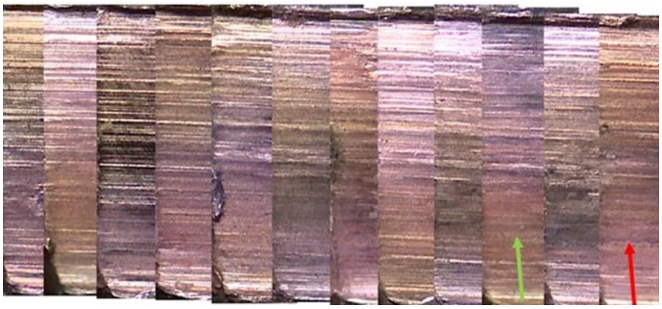

Figure 11: Illustration of the change in stria on the bullet as the barrel is sanded in 1" increments from the chamber towards the muzzle. Barrel 6 land #4 from left to right (chamber to muzzle): From left to right, pre-sanding tests 1 and 2, 1", 2", 3", 4", 5", 6", 7", 8", 9", 10". Green arrow indicates point of inconclusive; red arrow indicates point at which striations become different.

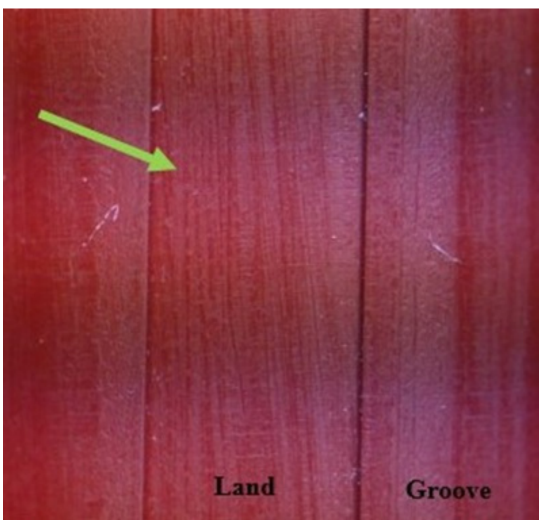

Figure 12: Post sanding cast of barrel #6 showing removal of reaming marks (Green arrow) in the land at 1 inch from muzzle (top) 20x total magnification.

that individual features on the muzzle end are more significant than defects at the chamber end of the barrel. The pilot of the crowning tool is the likely source of the change in individual characteristics.

Sanding the barrel completely removed the reaming marks in the barrel. However, the individual characteristics transferred onto fired bullets did not change as the barrel was sanded in 1-inch (25.4mm) increments until reaching 3-inches (76.2mm) from the muzzle end of the barrel. The last 2-3-inches (50.8mm to 76.2mm) of the barrel at the muzzle end had the greatest effect on the individual characteristics on the bullets, with the single largest change at the last 1-inch (25.4mm) of the muzzle. This supports the conclusion that while the bullet picks up marks as it travels down the barrel, these marks are overwritten by the individual characteristics in the last 1-inch (25.4mm) of the barrel.

Acknowledgments

A special thanks to Smith & Wesson, and its dedicated employees, for supplying the barrels used and for making themselves available to answer questions. This study would not have been possible without their dedication and professionalism.

This project was made possible in part through a grant funded by the Association of Firearm and Tool Mark Examiners and adapted from UAB thesis research IRB-300001647.

References

[1] Biasotti AA. Rifling Methods – A Review and Assessment of the Individual Characteristics Produced. AFTE Journal. 1981;13(3):34-61.
[2] Best BA, Gardner EA. An Assessment of the Foundational Validity of Firearms Identification Using Ten Consecutively Button-Rifled Barrels. AFTE Journal. 2022;54(1):28-37.
[3] Monson KL, Smith ED, Peters EM. Accuracy of Comparison Decisions by Forensic Firearms Examiners. Journal of Forensic Sciences. 2022;00: 1-15. https://doi.org/10.1111/1556-4029.15152
[4] Hall EE. Bullet Markings from Consecutively Rifled Shilen DGA Barrels. AFTE Journal. 1983;15(1):33-53.
[5] Matty W. A Comparison of Three Individual Barrels Produced from One Button Rifled Barrel Blank. AFTE Journal. 1989;21(2):370-374.
[6] Miller J. An Examination of Two Consecutively Rifled Barrels and a Review of the Literature. AFTE Journal. 2000;32(3):259-270.
[7] French D. Grain Boundaries. National Board of Boiler and Pressure Vessel Inspectors. https://www.nationalboard.org/index.aspx?pageID=164&ID=194. 1991. Accessed 2019 April 14.
[8] Monturo C. The Effect of the Machining Process as it Relates to Toolmarks on Surfaces. AFTE Journal. 2010;42(3):264-266.
[9] Walker J. Machining Fundamentals. The Goodheart-Willcox Company, Inc. Tinley Park, Illinois 2000.
[10] Hatcher JS, Frank JJ, Weller J, Samworth TG. Firearms Investigation, Identification and Evidence. The Stackpole Company. Harrisburg, Pennsylvania, 1957.
[11] Murdock JE. The Survival of Identifiable Bullet Striae

Caused by Defects in the Forward Rim of a Revolver Chamber. AFTE Journal. 1981;13(3):62-71.
[12] Smith TP, Smith AG, Snipes JB. A Validation Study of Bullet and Cartridge Case Comparisons Using Samples Representative of Actual Casework. Journal of Forensic Sciences. 2016;61(4):939-946.
[13] Smith J. Methods of Rifling by Manufacturer. AFTE Journal. 2011;43(1):45-50.
[14] Murdock JE. The Effect of Crowning on Gun Barrel Individuality. AFTE Journal. 1970;2(NL07):12-35.
[15] Voluntary Industry Performance Standards for Pressure and Velocity of Centerfire Pistol and Revolver Ammunition for the Use of Commercial Manufactures. Sporting Arms and Ammunition Manufacturers' Institute (SAAMI). December 14, 2015, Accessed April 14, 2019, https://saami.org/wp-content/uploads/2019/02/ANSI-SAAMI-Z299.3-CFP-and-R-Approved-2015-12-14-Posting-Copy.pdf.
[16] Correspondence with Smith & Wesson, January 2018.
[17] Tulleners F. Striae Reproducibility on Sectional Cuts of One Thompson Contender Barrel. AFTE Journal. 1998;30(1):62-81.