The effect of composition and morphological features on the striation of .22LR ammunition

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Abstract

The forensic firearm examiner is often asked questions such as 'what kind of gun was used' or 'was this particular gun used?' In order to answer such questions, the examination of the striae left on the bullet by the transit in the rifled barrel of a gun is paramount. Many variables concur in the formation of this striation pattern. In this paper, the effect of the chemical composition of the bullet was studied and correlated to the extent and quality of the markings left after shooting them with the same gun. Scanning electron microscopy and optical comparator microscopy equipped with 3D and profilometry modules were used as non destructive techniques with two main purposes. The first is to assist the firearm examiner in the choice of the ammunition most suitable for preparing the test bullets. The second is to propose an approach, crossing data from optical microscopy, profilometry and space-resolved chemical analysis, for explaining the morphology of striae, whether continuous or interrupted. Among the most notable results is the finding that commercial .22LR ammunition shows very wide interbrand, interlot and intralot variability. A selection of test ammunition solely based on the same brand and model used on the crime scene is therefore not suitable, urging the need for a more accurate choice, based on a preliminary chemical analysis. Intrasample variability was also pronounced within the same bullet, bringing about striae which were abruptly interrupted due to a change in the chemical composition of the alloy in neighbouring regions of the surface. Optical microscopy equipped with profilometry capability proved especially useful for explaining interruption of striae where composition was not involved, offering the forensic firearm examiner a powerful toolbox for completely understanding, interpreting and discussing the striation

patterns in casework, improving the efficacy, solidity and evidential value of the conclusions deduced thereof.

Introduction

In the context of firearm examination, ballistic identification deals with many problems, but one of the most important is to establish, mainly by microscopical observation [1-4], which gun was used to fire the bullets related to a certain crime. This analysis rests on the assumption that bullets fired through the same rifled barrel will show an array of markings which is peculiar to that particular firearm and to no others [4-6].

In a firearm shot, the bullet, passing through the rifled barrel, engages the lands and grooves, and this interaction brings about the appearance of a number of markings. Striae will therefore appear on the surface of the fired bullet which reflect the individual mix of defects and imperfections of the particular barrel through which it travelled. In addition to this mechanism, which brings about a reproducible set of striations, the complex series of events associated to a firearm shot produce a number of additional markings, which are less reproducible and can complicate the work of the firearms forensic examiner. Such markings can be conveniently divided into different categories [5,7]:

a) adventitious markings: random features due to the presence of debris or other impurities in the barrel;

b) axial markings, which are produced at the rifling lead or by the breech end of the lands and grooves, before the bullet starts its rotational movement;

c) marks due to poor rifling. These striations are related to defective or severely worn rifling, in which cases the rotation of the bullet is hindered;

d) skid markings which depend on the alignement and timing of the initiation of rotation of the bullet;

e) variations in cartridges: reproducibility of the striations depends greatly on the features of the fired ammunition, such as the pressure of the evolved gases, the size of the bullet and its material.

If on one hand some of these markings are due to random variables, which cannot be controlled and thus contribute to the uncertainty of the examination, on the other hand the last one deserves particular attention, because it is, at least partly, a controllable variable in the analytical process. In fact, good laboratory practice suggests that the test bullets, needed for assessing the peculiar features of the gun confiscated to the suspect, be fired using the same make of ammunition submitted as evidence [5]. However, this is not always straightforward, because rarely it is possible to identify the make if only the bullet is available, and so just physical features such as weight, calibre and type of bullet are considered in the selection. Moreover, as it will be apparent in the following of this paper, stark variations in the composition of ammunition of the same brand and model can appear. This in turn changes the response of the material to interactions with the barrel and may likely produce variations in the striation pattern.

The purpose of this article is assessing the viability of scanning electron microscopy (SEM) as a non destructive technique able to assist the firearm examiner in the choice of the ammunition most suitable for preparing the test bullets. A further objective was to gain a picture of the variability of the composition of commercial .22LR ammunition, and how this variable composition affects striations.

In spite of common thinking, .22 LR firearms have indeed killing capabilities and are widely used for criminal intents, also in renowned cases. In 1968, Robert Kennedy was killed with a Iver-Johnson Cadet 55-A, an eight shots .22 LR revolver; the most famous Italian serial killer, the Monster of Florence, used a Beretta .22 to kill sixteen people, from 1968 to 1975; and in 2016 Anis Amri used, during and after the terrorist attack in Berlin, an Erma Werke EP552, a calibre .22LR semiautomatic handgun based on the Walter PPK model. The large use of .22 calibre in crimes has several explanations. Firstly, it's very common, both for handguns and for rifles. It is not easy to find statistic about firearms diffusion, but 17% of handgun produced from 1991 to 1993 in United States, and 18,3% of handgun stolen at 1995, were in calibre 22; in 1985 14% of homicides in Philadelphia, and 16% in 1990, were committed with calibre 22 [8]. Moreover, it has been reported that 16% of criminal who bought a firearm in US with the purpose of committing a crime, chose a .22 calibre [9]. The diffusion is helped by several factors: it's a cheap ammunition, it requires cheap weapons, has little recoil and it's used in official shooting competition.

Moreover, .22 calibre, despite its little kinetic energy (like golf balls or tennis balls thrown by rookies), has an energy density comparable to that possessed by more powerful ammunition. Energy density is a much more interesting quantity when dealing with wound ballistic [10], and this explains why the terminal and wound effects of .22 are, despite its lightness, often so effective.

The identification of firearms is very difficult with .22 LR bullets. Firstly, this kind of bullets is hard to analyse of their small size. Furthermore, they tend to be heavily marked, with adventitious markings, axial markings and skid markings often present. Moreover, the effects of poor rifling, of variations in chamber pressures, of bullet diameter and of surface metal are crucial for a significant examination [7]. Finally, the ratio between the surface impressed by rifling and the total volume of the bullet is higher than usual and so the surface analysis is really important. Despite its wounding capabilities and the problems that arise during its analysis, few forensic firearm identification papers studied .22 LR calibre.

A further element of novelty of this paper is actually the use of SEM for obtaining information on the chemical composition of bullets, whereas this technique in the ballistics field has traditionally been limited to morphological studies [11-13] and to gunshot residue determination [14-16]. The issue of elemental composition of bullets has been quite thoroughly investigated [17-28], but always with atomic spectroscopy or mass spectrometry techniques. The main aim of such studies was estimating if the composition of a bullet could be a significant feature for linking a fired bullet to the ammunition seized to a suspect. Hogg and coworkers recently analysed the chemical composition of lead free ammunition, with the aim of assessing the non toxicity of the particles discharged by their firing [29]. The complementary use of morphological and compositional information coming from SEM and traditional examination of markings through optical microscopy, in order to obtain a more complete picture and interpretation of striations, is still an underinvestigated field.

Experimental

Samples

In this study, two brands of commonly used .22LR ammunition were purchased in local armory shops. Of each brand, boxes marked with different lot numbers were acquired, as summarised in Table 1.

Table 1. Samples examined in this study

Brand	Model	Lot no.
CCI	Blazer	324X29*
CCI	Blazer	326B32*
Fiocchi	TT Sport	5810025
Fiocchi	TT Sport	5803003

* For CCI ammunition lot numbers were hardly visible, some misunderstood numbers are possible

Such ammunition were fired with the same Tanfoglio model Force 22L handgun, with a steel barrel calibre .22LR. Bullets were fired into clean, untreated cotton batting. Two sets of samples were prepared for each lot of ammunition, namely shots performed with clean gun and with fouled gun conditions. For the clean gun tests, the firearm was carefully cleaned after every shot. The fouled gun conditions were simulated recovering the bullet after having fired at least 100 shots before.

Morphological and chemical analyses were performed on a FEI Quanta 200 scanning electron microscope equipped with a EDAX energy dispersion spectroscopy detector. Given the conductive nature of the specimens, no coating was necessary. At least 3 bullets in each case were examined. The reported composition data are the average of such repetitions.

Striation of the bullets was examined with a Leica FSC comparator microscope, equipped with 3D and superficial topography Leica Map Start module.

Results and discussion

Scanning electron microscopy associated to Energy Dispersive Spectroscopy (SEM-EDS) was employed to investigate the composition of the bullets considered in this study. To the knowledge of the authors, all previous works on bullet composition made use of traditional elemental analysis techniques, such as atomic absorption or emission, mass spectrometry or neutron activation [17-28]. On one hand, these analytical approaches are far more sensitive and more suitable for a proper quantitation of elements even in trace amount. On the other hand, they normally require digestion and solubilisation of the sample and are thus destructive. Even when destruction of the sample can be avoided, such as for example in laser ablation techniques, they do not allow spatially resolved elemental analysis. Since the purpose of this study was that of detecting possible inhomogeneities in the chemical composition of bullets and relating them to their striation behaviour, the non destructivity and the spatially resolved chemical analysis made possible by SEM-EDS were considered optimal. Each bullet was divided into regions delimited by cannelures, numbered in increasing order starting from the tail area to the tip. Table 2 reports the results of SEM-EDS data obtained.

Table 2. Composition data of the examined ammunition

		Composition (%)			
Brand	Lot no.	Area 1 (tail)	Area 2	Area 3	Area 4 (tip)
CCI	324X29	Sb: 1.8 ± 1.0	Sb: 1.8 ± 1.0	Sb: 1.1 ± 1.0	Sb: 2.7 ± 0.4
CCI	326B32	Sb: 2.7 ± 0.3	Sb: 2.8 ± 0.3	Sb: 2.7 ± 0.3	Sb: 2.9 ± 0.6
Fiocchi	5810025	Sb: 2.3 ± 0.9	Sb: 1.8 ± 0.8	Sb: 1.2 ± 1.1	Sb: 2.3 ± 0.8
Fiocchi	5803003	Sn: 2.4 ± 0.3 Sb: 0.3 ± 0.1	Sn: 2.1 ± 0.4 Sb: 0.6 ± 0.2	Sn: 1.8 ± 0.3 Sb: 0.2 ± 0.1	Sn: 2.0 ± 0.7 Sb: 0.4 ± 0.2

.22 LR ammunition is basically composed of lead. The alloy and the quantity of the minor component is formed mainly in the smelting/refining step of the process and it does not significantly change during the bullet manufacturing phase [21,26]. Three basic types of lead are used in bullet manufacturing [21]: lead-tin alloys, which due to their low melting point and fluidity of their molten phase are mostly employed for mould casting bullets; lead-antimony alloys, mainly used for extruded or swaged bullets, in which antimony improves the hardness of the metal; unalloyed lead, which is a very soft material, used for the most inexpensive ammunition. To prevent fouling of the firearm, bullets made with unalloyed lead are often coated with a thin layer of copper or copper-zinc alloy, in a process called gilting.

Although it is beyond the scope of this paper to discuss the metallurgy of lead alloys, for which the reader is directed to more specific literature [26 and references within], it must be noted that these alloys should not be seen as completely homogeneous materials. Segregation and diffusion of trace elements within the bulk of the material, to and from grain boundaries, are common and ubiquitous phenomena. The extent to which such modifications of composition happen, depend on the conditions of the smelting, refining, extrusion and/or casting processes, and especially on the temperatures and rates of heating and cooling.

More importantly, segregation of minor and trace elements is not a concern in the ammunition industry, because such phenomenon impacts on the structural or corrosion resistance features of the metal, all characteristics which are of no importance for a bullet [21]. Several studies demonstrated that not necessarily all the bullets in a given box share exactly the same chemical composition [23,30]. However, usually the major alloy components such as tin or antimony have a functional role in the material and thus they are expected to be more strictly specified. Surprisingly, in this study a wider availability emerged. As may be seen in Table 2, it happened that bullets marketed with the same brand name, pertaining to different lots, were actually made with two different alloys: lead-antimony in the case of Fiocchi TT Sport Lot 5810025 and lead-tin in Fiocchi TT Sport Lot 5803003.

A number of notable features emerge from Table 2. The large errors associated to the composition data of CCI Lot 324X29 is due to the fact that two of the examined samples had an average Sb content of about 2.5%, quite homogeneous over the whole length of the bullets. One bullet, however, had a much lower Sb content, hovering around 0.5%, also in this case without large variations over the surface of the artefact. Replicates made on bullets from the same box confirmed the existence of this bimodal distribution of the composition of the alloy associated to this lot. It has been previously reported [23,30] that bullets with different composition can coexist in one same lot of ammunition. The CCI lot 326B32 on the contrary was much more homogeneous in composition, and all the analysed bullets shared a Sb content of about 2.7%.

Fiocchi ammunition had a consistent intralot average composition. These bullets, however, were much more variable intra-sample. In other words, different regions of the same bullet showed very variable percentages of the minor component off the alloy. In particular, in the region immediately adjacent to the tip, the metal was much richer in lead, and consequently poorer in the minor component, than in the rest of the bullet. On the other hand, the tip was, in all considered ammunition, the part of the bullet richest in antimonium or tin. As mentioned above, Fiocchi also displayed a very significant change in composition between different lots of the same kind of ammunition. Table 2 shows that Fiocchi Lot 5810025 was made with a lead-antimony alloy, whereas Fiocchi Lot 5803003 was made with lead-tin. In addition to the chemical composition, Fiocchi and CCI ammunition exhibited differences also on the morphological side, which in turn reflected variations in the manufacturing process of bullets. Fiocchi appeared to have a layered structure, whereas CCI was more solid and monolytic (Figure 1).

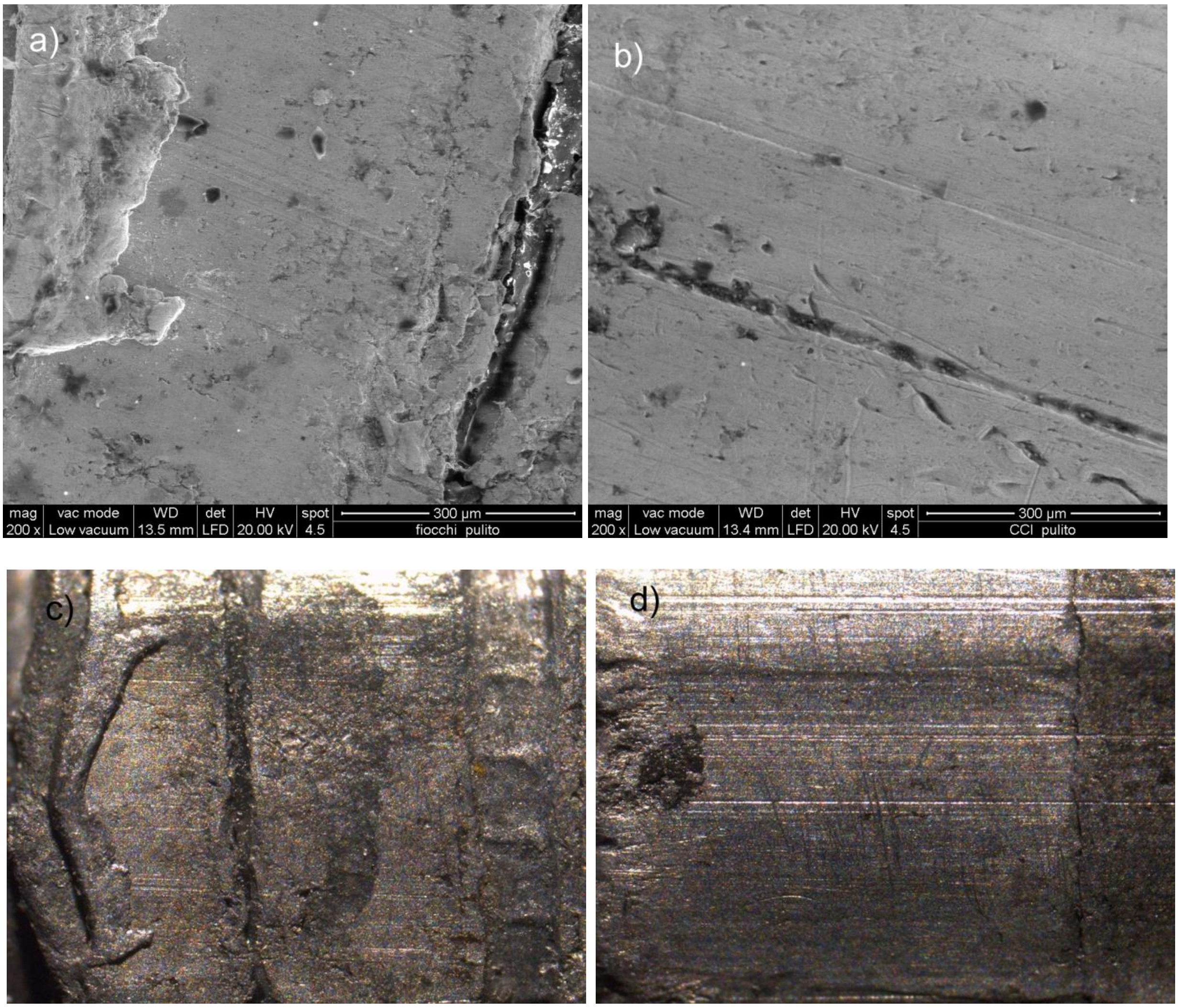

Figure 1. Microphotographs of Fiocchi lot 5810025 (a and c) and of CCI lot 324X29 (c and d). Particulars a and b were acquired by SEM, photographs c and d were obtained by optical microscopy.

The effect of such differences in composition and surface morphology of the bullets was, as expected [5], reflected in the striation patterns when shot from the same firearm. Different compositions of the alloy bring about different mechanical properties of the metal.

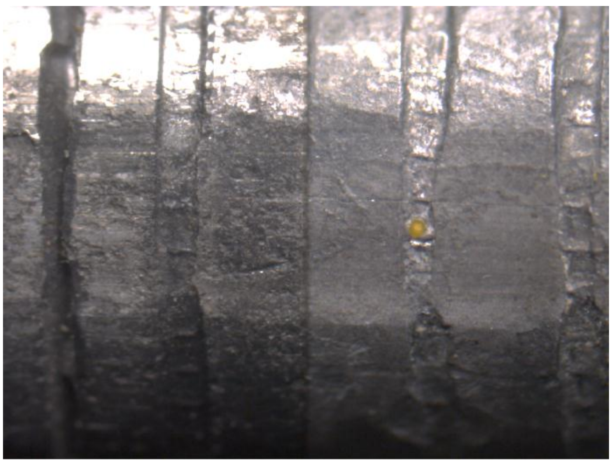

Figure 2. Comparison microscope image of Fiocchi lot 5803003 (left) and of Fiocchi lot 5810025 (right), fired in clean gun conditions.

Figure 2 shows a comparison of two Fiocchi bullets of different lots, fired in clean gun conditions. The rough surface of the lead-tin alloy of the lot 5803003 specimen is very poorly marked, whereas the striation pattern of the Fiocchi lot 5810025, made of lead-antimony, is clearer and richer in information. Note that surfaces with different roughness and composition reflect light in quite different ways, further complicating the comparison step [1].

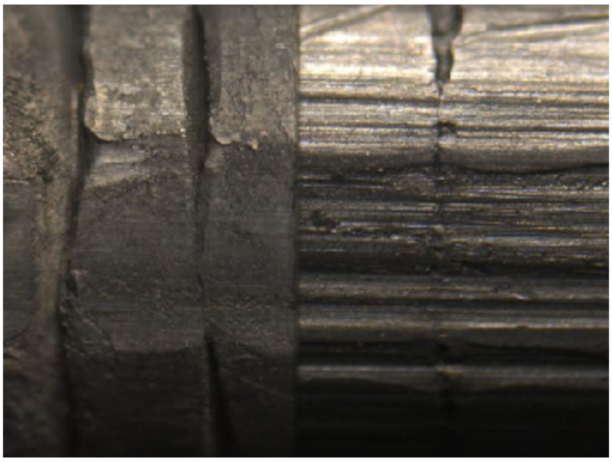

Figure 3. Comparison microscope image of Fiocchi lot 5810025 (left) and of CCI lot 324X29 (right)fired in fouled gun condition.

Figure 3 compares a Fiocchi lot 5810025, which had a Sb% of about 1.5-2%, with a CCI lot 324X29 bullet with a particularly low Sb content, around 0.5%. Both ammunitions were fired in fouled gun conditions. The differences in morphology are stark and evident. The CCI bullet is so severely marked that even the determination of firearm class characteristics is jeopardised, because some of the necessary parameters are impossible to accurately measure: the width of land and grooves, the degree of twist of rifling and the depth of grooves. A low Sb content is associated to a softer lead alloy, which therefore is much more prone to marking. This is confirmed it the same type of bullet is fired by a clean or a fouled gun (Figure 4).

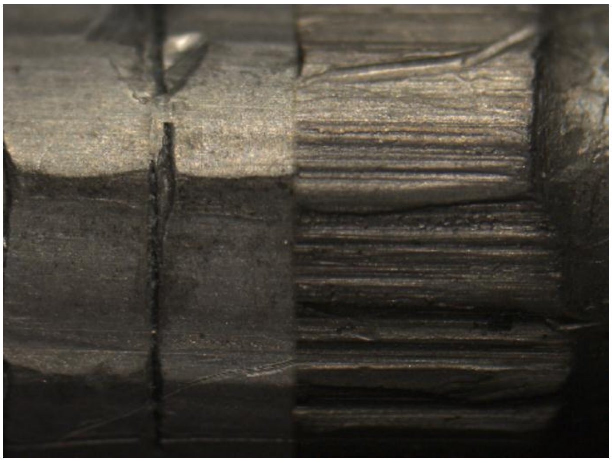

Figure 4. Comparison microscope image of CCI lot 324X29 fired in clean gun (left) and in fouled gun (right) condition.

If shot with a clean gun, the bullet is striated and very well analysable. As seen before, the effect of a dirty barrel is that of overmarking the metal, greatly complicating the task of the examiner.

The spatial resolution of SEM allowed to investigate in further detail the role of composition on the marking of the bullets. Figure 5 shows a detail of a CCI lot 326B32 bullet fired with a clean gun. The composition of the alloy was sampled along intermittent striae.

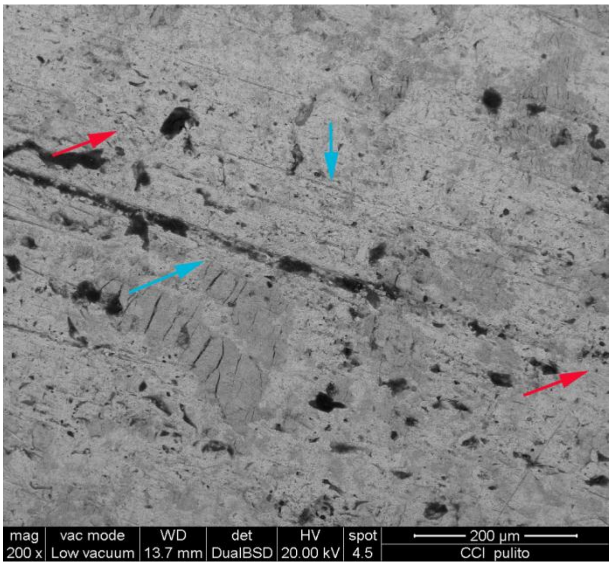

Figure 5. SEM micrograph, obtained with the backscattered electron detector, of a CCI lot 326B32 fired in clean gun conditions. Arrows indicate the position where elemental analysis was performed by EDS. Red arrows indicate regions where striation was absent, blue arrows where striation was present.

The Sb content where the striation was marked was between 1 and 2%, whereas the unmarked regions had a higher Sb content, higher than 3%. A similar behaviour was recorded for Fiocchi bullets. A harder material was obviously impervious to marking. The possibility to interpret the reason why a particular striation is interrupted is a very attractive asset for the forensic scientist, because it helps strengthen conclusions and base them on a more solid conceptual basis.

Another reason for interruption of a striation is the morphology of the surface. Figure 6 shows an optical micrograph of a Fiocchi lot 5803003 sample.

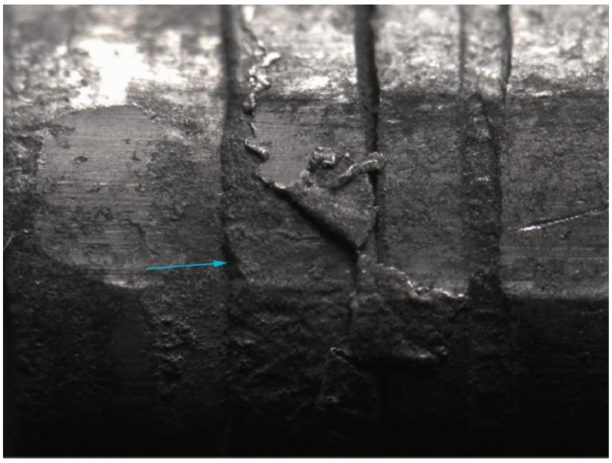

Figure 6. Micrograph of a Fiocchi lot 5803003 bullet fired with a clean gun. The arrow shows the area where flaking occurred.

The layered structure of the metal is evident. As may be seen, flaking occurs in the area designated by an arrow in Figure 6, exposing the layer underneath. The morphology of such surfaces is very different. The coated areas have a very smooth appearance, and the striation is very neat and clear. On the contrary, the inferior layer is much rougher, with a much less intelligible morphology, and no significant marking appeared. Such variability in the quality of marking is well known in plated bullets, where some of the coating can be removed as it passes through the bore [31] It should be noted that in this case differences in marking cannot be ascribed to differences in composition, because the amount of tin throughout the area is constant. In this case, flaking exposes an area, which is depressed with respect to the surrounding region, and thus its interaction with the barrel will be less significant. Figure 7 shows another area of a Fiocchi lot 5803003 bullet, in which, like in Figure 6, two different regions can be clearly identified: a rough area on the left and a smooth, coated area on the right. The average roughness of the rough area, calculated along the green line of Figure 7, was 15 µm, that of the smooth area, evaluated along the red line of Figure 7, was 2.8 µm.

The profile in Figure 7 shows how the rough region, which is correspondent to the flaked metal, is also located on a depression with respect to the smoother part. Despite the two regions share the same composition, the coated, elevated area is marked and shows several striae, whereas the left portion of the picture is unmarked due to its lower elevation and thus to the less intimate interaction with the barrel.

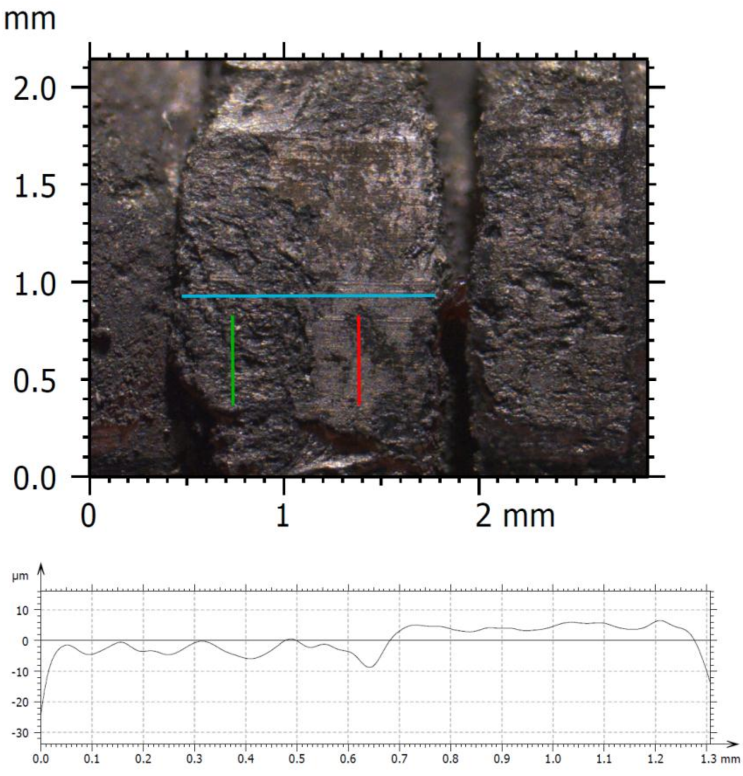

Figure 7. Particular of a Fiocchi lot 5803003 bullet fired with a clean gun. The profilometry on the bottom of the picture is measured along the blue line. The green and red lines are the lines where rugosity was evaluated for the rough and smooth areas, respectively.

Conclusions

In this work, the intrasample, intralot, interlot and interbrand variability in the composition of commercial .22LR ammunition was assessed. The aim was understanding the extent of the influence of the composition of the alloy on the striation pattern and thus on the reliability of the firearm identification conclusions deduced thereof.

It was shown that SEM-EDS is a very useful tool for selecting suitable ammunition to prepare, by firing with the suspect gun, test samples to be compared with the evidence found on the crime scene.

The present study showed that just basing such choice on the brand of the casings retrieved from the crime scene is a very risky procedure. For example, imagine that on the scene of a shooting incident Fiocchi .22LR shells were found. If the forensic firearm examiner shot test bullets of a random Fiocchi lot, chances exist that he could compare lead-antimony bullets with lead-tin composition specimens. The best case scenario is that the analysis would be severely complicated, the worst case scenario would be an incorrect conclusion, probably a false negative. A preventive, non destructive test by SEM-EDS would avoid such inconvenience.

A further advantage of the combination between SEM-EDS and the optical microscopy techniques, either traditionally employed or in coordination with 3D and profilometry modules, is the possibility of interpreting the reason why striae appear in some regions of the bullet and disappear in others and to understand which variables are involved in this behaviour. The interpretation obtained thereof would make the firearm examiner's conclusions more objective and the evidential value of the findings more solid.

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