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Plumbum Microraptus: Definitive Microscopic Indicators of a Bullet Hole in a Synthetic Fabric*

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KEYWORDS

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ABSTRACT

A central question in a criminal forensic investigation involved a hole (later termed a "defect") observed in a garment and whether it was produced by a bullet or some other means. The individual wearing the item was known to have fired or been in the vicinity of a firearm that was discharged, rendering the presence or absence of gunshot residue on the garment irrelevant. The micromorphology and elemental composition of the severed fiber ends in a series of exemplar bullet holes were characterized to identify specific physical indicators of the bullet-garment interaction on a microscopic scale. This study confirms prior research indicating that fiber failure, due to the high-energy transfer from a bullet to a synthetic fabric, is consistent with a high-speed tensile fracture mechanism, which results in characteristic fiber-end micromorphology due to partial melting. In addition, scanning electron microscopy (SEM) imaging and elemental analyses by energy-dispersive X-ray spectroscopy (EDS) provide direct evidence of the capture of detectable microscopic lead particles both on and within the melted fiber ends, a process termed here as plumbum microraptus (microscopic lead capture). These lead particles are observed primarily as planar abrasion fragments but also as spherical particles, the latter of which further illustrates the high-energy transfer. Through the study of individual broken fibers from within a suspected bullet hole, these characteristic indicators provide a minimally invasive and direct means to definitively associate or (equally important) dissociate a fabric defect with a bullet perforation.

INTRODUCTION

The question of whether or not a bullet has perforated a fabric is a discrete question with relevance to the field of forensic science. In many instances, the presence of secondary evidence such as blood, tissue or an associated wound can render such a question trivial. In close range events, the presence of primer gunshot residue (pGSR) on a fabric can provide strong evidence of a ballistic association. At greater distances, a dark ring of debris, called "bullet wipe," is often observed (Figure 1) or can be detected (even on dark clothing) and has been stated to consist of traces of bullet metal, lubricant and residue from the gun barrel (1, 2) (Figure 2). In some cases, bullet wipe may not be visible or the presence of pGSR on a garment may not be sufficient to provide a definitive answer as to the origin of a particular hole. For example, in the event that an alleged bullet hole was located on a garment worn by a person who fired or was in the vicinity of a discharged firearm, such ancillary evidence may not be

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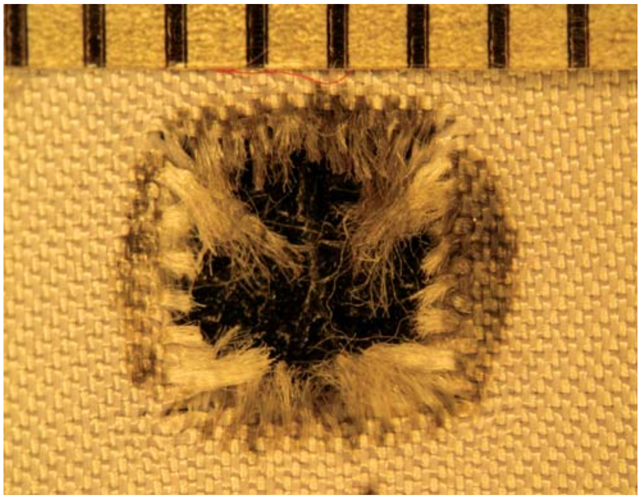

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Figure 1. This hole in a woven cotton fabric was made by a 7.62 mm full metal jacket bullet. The discoloration at the perimeter of the hole is an example of "bullet wipe," the deposition of bullet and barrel material transferred as the bullet perforated the fabric. Shown is the entry side of the hole, which has the greatest concentration of deposited material and can be more closely examined microscopically to assess fiber failure mechanisms and spectroscopically to identify the foreign material. The presence of lead can also be determined at such a site by using the classic sodium rhodizonate test. Each line on the scale equals 1/16 inch.

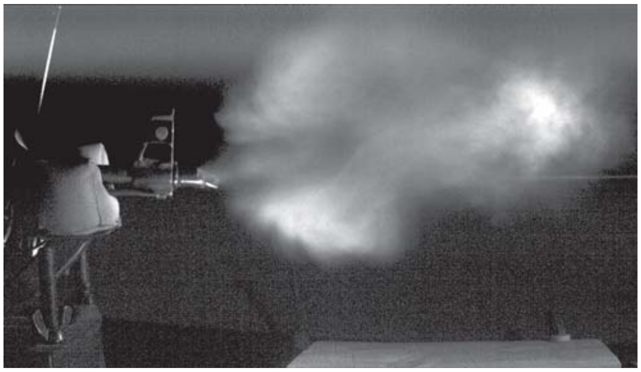

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Figure 2. Gases shown were emitted at the muzzle of an AK-47 rifle one millisecond after the bullet exited the barrel. This plume contains a rich supply of lead, which originates from both the primer (containing lead styphnate) and the base of the bullet that is not enclosed by the jacket, thus exposing the lead core (seen in Figure 3) to the hot gases impinging on the base. When the firing sequence begins, the firing pin strikes the primer, creating a shower of sparks that ignites the smokeless powder, which burns rapidly, generating a huge volume of hot gas. Some of the exposed lead is vaporized by the hot gases impinging on the base of the bullet and results in the heavy contribution of lead in the plume exiting the muzzle. A portion of this vaporized lead is left behind in the barrel and condenses inside the barrel circumference when the temperature cools, so when the next bullet travels down the barrel it can carry with it lead from prior discharges.

conclusive. In such cases, we have demonstrated that a direct microscopical examination of the hole, often termed the "defect area" (in contrast to the area surrounding the hole), can provide a definitive answer to this question.

This approach is based on a fundamental principle of forensic science, which suggests a strong likelihood of transfer between objects that come into contact with each other. In the case of a bullet that perforates a synthetic fabric, at least two possible types of transfer are hypothesized to occur at the interface of the bullet and fabric. The first is a transfer of energy, which results in fiber (and fabric) failure; the second is a transfer of material from the bullet to the broken ends of the fibers (or the transfer of polymer to the bullet).

The energy transfer resulting in high-speed synthetic fiber breakage, due to an event such as a bullet perforation, has been mechanically classified as a "high-speed tensile break" (3) or "rapid shear." Physically, such a break can be understood by considering the brief interaction of a fired bullet as it passes through a synthetic fabric whereby a portion of the kinetic energy is transferred from the bullet to individual fibers of the fabric. This tension mechanism stretches and eventually breaks the fiber. The energy transfer is sufficient to melt the stretched portion of the thermoplastic polymer comprising the fiber. This result has been observed in several forensic research efforts specifically involving the perforation of synthetic (nylon or polyester) textiles by a bullet (4, 5). This mechanism does not apply to cellulose-based fibers such as cotton or rayon, which do not melt (6).

It is also anticipated that particle transfer will occur during the bullet-fiber contact period, resulting in the presence of firearms-related particles around this area and embedded in the molten fiber. While SEM/EDS and atomic absorption spectroscopy have been used to identify lead (Figures 3 and 4) and primer particles (Figure 5) in the vicinity of bullet holes (7), it is hypothesized that such particles will also be found on and embedded within the broken fiber ends. Although the distinction between "around" and "embedded within" is minor, the latter provides definitive evidence that the fiber end was created by a high-speed lead or lead-laden object and eliminates the argument of in-

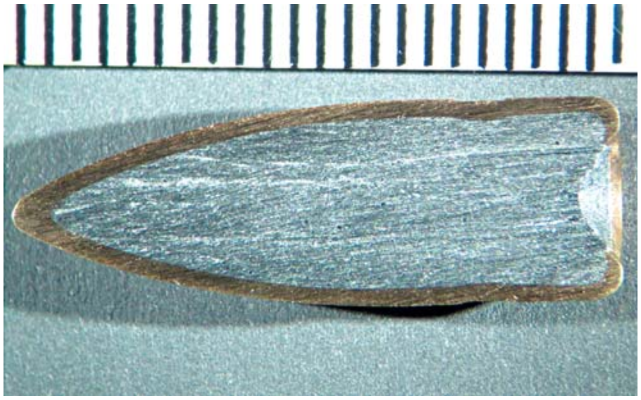

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Figure 3. A full metal jacket bullet that was removed from a 7.62 x 39 mm cartridge has been cut in half lengthwise to reveal its construction. Despite the name "full metal jacket," the base of the bullet is not jacketed and, therefore, the exposed lead is susceptible to attack by the energetic gases generated by the burning propellant. These gases impinge upon the exposed lead, some of which is volatilized, allowing it to migrate to the outside surface of the bullet's jacket; it can also condense on the inside of the gun barrel. This lead becomes one source of material that can be deposited at the perimeter of a bullet hole. (Scale is in millimeters.)

advertent contamination from non-GSR sources, e.g. airbags (8), fireworks (9), brake pads (10), etc. Confirmation of this hypothesis in conjunction with the distinct fiber-end morphology, as demonstrated in this research, provides a simple and definitive means to confirm or refute the statement that a hole was produced by a bullet using microanalytical methods readily available in most forensic laboratories.

EXPERIMENTAL

The bullet holes were initially examined by stereomicroscopy with Leica EZ-4D and Wild M5 stereomicroscopes using a combination of transmitted, oblique and co-axial illumination. Isolated individual fibers were mounted on glass microscope slides in various refractive index oils (n=1.520 and n=1.660 at 20° C). The preparations were then examined by transmitted polarized light microscopy using an Olympus BH2 microscope. Fibers were mounted on carbon tabs on aluminum stubs, which were then gold-coated for SEM analysis. SEM analysis was conducted using a JEOL 6490LV SEM with a Thermo Noran System Six Silicon Drift Detector at 20keV with a spot size that varied from 20 to 65 (nominal value) with backscattered electron (BSE) and secondary electron (SE) imaging detectors.

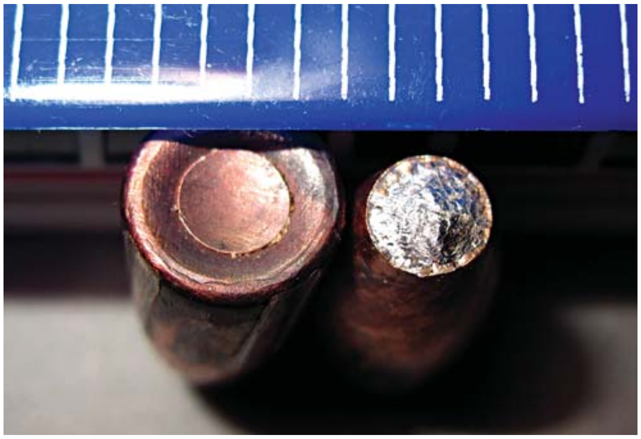

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Figure 4. Two unfired 7.62 mm soft-point bullets, one is base up (left) and the other is base down (right). The base-up bullet reveals that the jacket material continues around the bullet's base, sealing off the lead core. The base-down bullet shows that the jacket does not extend fully to the tip, leaving exposed lead to interact with the object that the bullet impacts (therefore, the name "soft point" bullet). Similar to the mechanism described in Figure 3, this lead becomes one source of material that can be deposited at the perimeter of a bullet hole. (Scale is in sixteenths of an inch.)

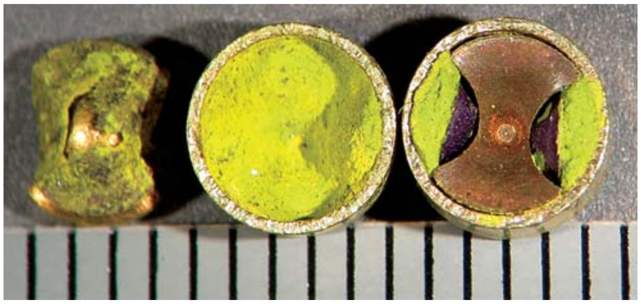

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Figure 5. Ammunition primer removed from an unfired cartridge is shown intact on the right. A similar primer is disassembled to reveal its two main components, the anvil (left) and the cup (center). The yellow mustard color is a result of the lead styphnate initiator. When struck by the firing pin, the impact-sensitive composition is crushed between the inside of the cup and the anvil, igniting it and sending a shower of sparks into the body of the cartridge to then ignite the smokeless powder. These sparks contain combustion by products of the lead styphnate, thus contributing lead to the system. Even if the jacket seals off the lead core of the bullet (as in Figure 4), the lead contribution from the primer will present a source of lead that can be carried with the bullet to the impact site. (Scale is in millimeters.)

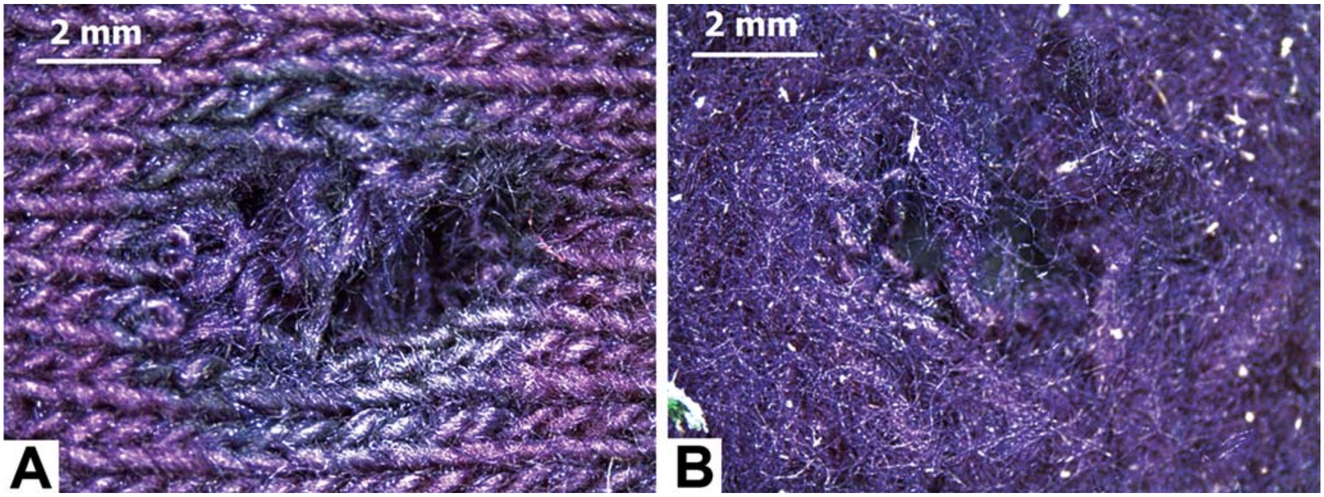

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Figure 6. The entry (6A) and exit (6B) sides of a single-bullet perforation in a cotton-polyester blended fabric. The entry side (6A) shows a ~2 mm wide annular discoloration that surrounds the hole, which is generally referred to as "bullet wipe."

RESULTS AND DISCUSSION

Exemplar Preparation

An exemplar fabric containing multiple entry and exit points was prepared for this examination by firing Wolf ammunition (7.62 x 39 123 GR. SP, steel jacketed, lead bullet) from an AK-47 rifle at a distance of 3.5 meters normal to the target at an air temperature of 30° C through a 70% cotton and 30% polyester (polyethylene terephthalate) dyed sweatshirt fabric. The fiber composition was confirmed by polarized light microscopy (PLM) and Fourier transform infrared microspectroscopy (FTIR) (6). The entry and exit side of one bullet perforation in the fabric is shown in Figure 6. The entry side of the hole (Figure 6A) shows a ~2 mm wide annular discoloration or staining that surrounds the hole, which is generally referred to as "bullet wipe" (4). Stereomicroscopy was used to determine and document the size of the holes (~0.5 cm), their relatively round shape and to observe a distinct directionality imparted to the broken threads, which are consistent with, though not definitively indicative of, the direction of bullet travel. (Fiber direction may vary in many cases due to removal of clothing and other factors.)

Fiber-End Isolation and Preparation

Once located by stereomicroscopy, a more detailed analysis of the frayed fibers was conducted at higher magnification by PLM and SEM. Prior to this, it was necessary to isolate individual fibers for analysis while tracking the end formed by the bullet. Depending on the sample and details of the case, specimens can be prepared in a variety of ways. For SEM, the simplest method is to excise a 2.5 x 2.5 cm fabric square containing the hole in question. In this way, it is possible to study an entire hole in the SEM. The drawbacks of this method are that the broken fibers are not ideally oriented in a direction that is optimal for imaging their ends, and in forensic casework, isolation of an area of this size is not generally an option due to evidence preservation requirements.

For these reasons, single fibers were individually isolated and studied. A single fiber of interest was located under the stereomicroscope and held with a pair of forceps approximately 5 mm from the broken tip (taking care not to touch the broken end). Prior to cutting off the thread from the garment, the fiber to be excised was marked (~10 mm from the broken tip) using a fine-tipped permanent marker while observing under a stereomicroscope. A cut was then made through the marker line, effectively isolating the fiber of interest. A benefit to this method is that the freshly cut ends (both that on the isolated fiber and the end remaining in the fabric) are both marked providing a semi-permanent indicator of the cut ends. This ensures that any future analysis is not confused by razor-cut fiber ends.

Fiber-End Characterization

Characterization of the isolated fibers by PLM was conducted using temporary mounts in refractive index oil (n=1.520). In this way, the generic class of the fiber can be easily identified by its optical properties (6) and, if necessary, washed in xylene, dried and

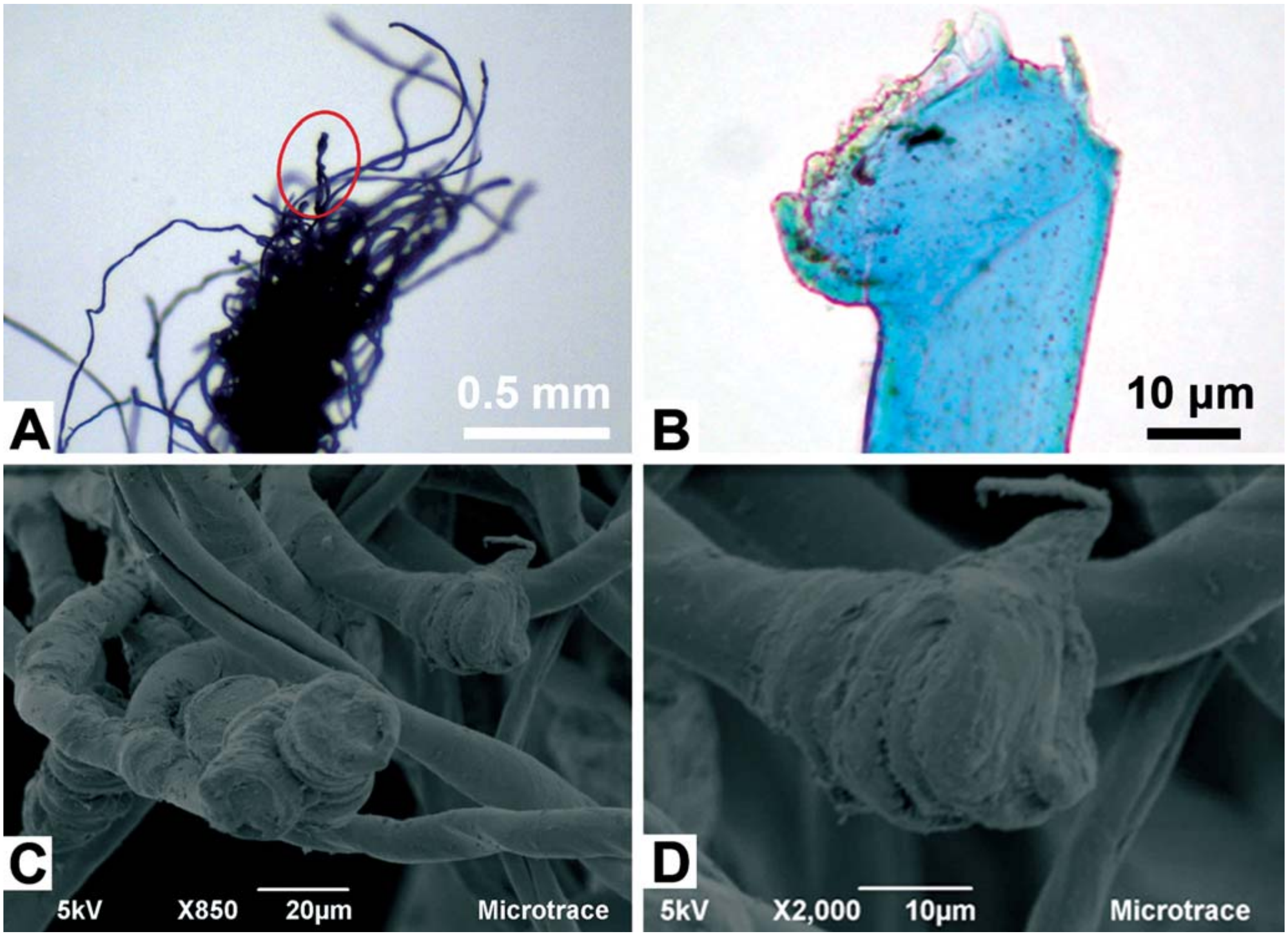

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Figure 7. **7A:** A stereomicroscope image shows yarn composed of multiple fibers that were all severed by the bullet perforation. The red circle highlights a group of fibers that were fused together as a result of the high-energy transfer that occurred during perforation. **7B:** A transmitted light image of a broken polyester fiber end shows the characteristic globular end resulting from a high-speed tensile fracture mechanism. **7C** and **7D:** Multiple fiber ends observed in secondary electron imaging; **7C** shows fused fiber ends. **7D:** The result of a stretch, fracture and recoil due to a high-speed, high-energy fiber break are captured in the morphology of a broken fiber end.

mounted for SEM analysis (though care should be taken with respect to fiber orientation because xylene will dissolve the orientation mark on the fiber).

SEM analysis was performed in various configurations using a JEOL 6490LV tungsten SEM. Uncoated fibers were successfully examined via backscattered electron imaging in variable pressure mode at 5–20 kV (30–50 Pa). While serviceable, fibers still charged at times under these conditions make the highest quality documentation difficult. For the purposes of publication, fibers were gold coated and observed without issue in both BSE and SE imaging modes. The gold coated fibers were generally preferable for study, documentation and elemental analysis. Despite the thin gold coating, metallic particles of interest (e.g. lead, chromium, iron *etc.*) were easily located in BSE imaging and readily characterized by EDS (as demonstrated here).

Morphology

Indicators of high temperature alteration are visible even at relatively low magnifications obtainable by stereomicroscopy, such as the fusing of multiple fibers shown in Figure 7A. In Figure 7B, the bulbous end typical of a severed fiber resulting from the rapid shear mechanism is shown as observed by PLM. Based on the failure mechanism, which results in partial melting and recoil of the elongated fiber prior to cooling, this characteristic end morphology has been

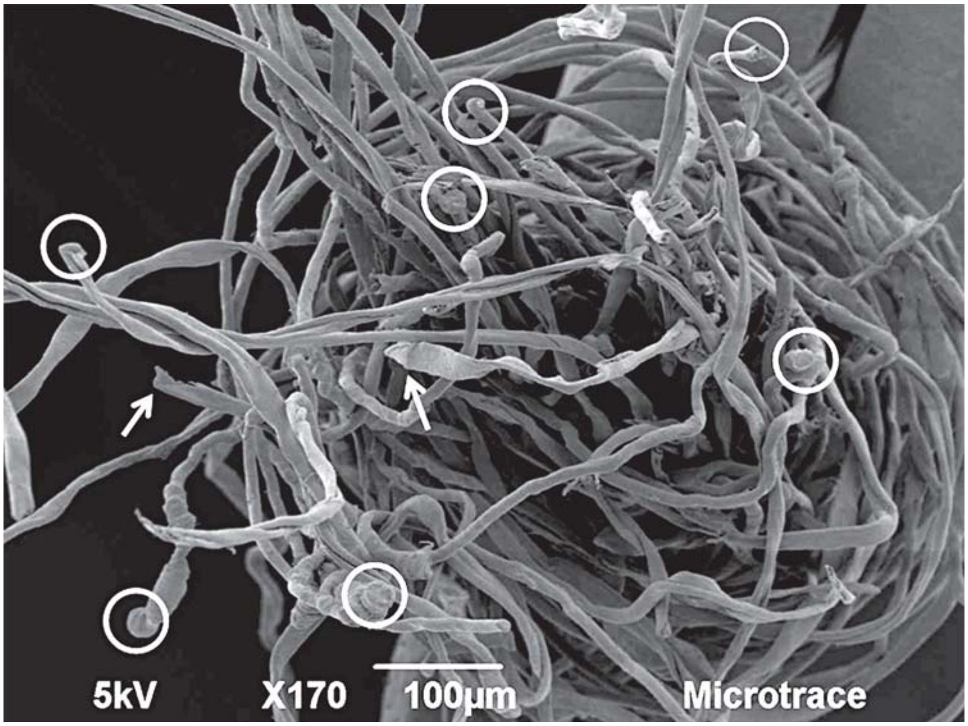

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Figure 8. A SE-SEM image of a single severed yarn shows numerous polyester ends (circled) all of which have globular ends characteristic of a high-speed, high-energy fracture mechanism. Arrows point to broken cotton fibers, which do not have globular ends.

termed a "globular" end. In general, the globular ends of the fibers show remarkably decreased birefringence when observed between crossed polarizers, which are consistent with prior findings (4, 5). This is expected, due to the loss of orientation when the newly formed fiber ends melt and rapidly cool without any specific means of reorientation.

While indications of globular ends can be observed by PLM, secondary electron imaging in the SEM provides more definitive evidence of the melting, stretching and rebounding that occurs when a thermoplastic fiber undergoes rapid shear. Figure 7C shows the melted globular ends of several fibers. In Figure 7D, the stretch, fracture and recoil resulting from a high-speed, high-energy fiber break are captured in the morphology of a broken fiber end as illustrated by the roughly annular compression marks near the globular end. Cotton (and other cellulosic) fibers do not melt and would not be expected to show such features, which are characteristic of a thermoplastic fiber. However, such fibers, which are often blended with synthetics in a fabric, are readily identified by PLM or SEM by their optical properties and morphology.

A SE-SEM image of a single, entirely severed thread (composed of many twisted fibers) isolated from the bullet hole is shown in Figure 8. Examination of this particular thread by stereomicroscopy, PLM and SEM shows that all of the broken polyester fiber ends in this cluster are globular. In total, more than 90% of the severed synthetic fiber ends counted in these bullet holes show distinct globular ends.

Particle Transfer

By transmitted light, visible discoloration in the form of dark opaque debris on the severed fibers in the bullet hole is apparent (Figure 7B). By reflected light, these same fragments show a dull metallic luster, which is consistent with the appearance of fine lead particles. This surface debris has a more irregular particle size distribution and is clearly distinguishable from the smaller, transparent TiO_2 inclusions that are added to many synthetic fibers as a delustrant.

Because it was anticipated that these metallic particles were related to bullet lead, they were studied by BSE imaging. Figure 9A shows the distribution of lead particles on the severed fiber end where lead-rich particles are indicated by their high contrast (white) against the lower average atomic number of the fiber and background of the image. Elemental analysis by EDS confirms that all of these particles are lead-rich. Figure 9B shows one particle that contains additional detectable iron and chromium, indicating it is a stainless steel particle.

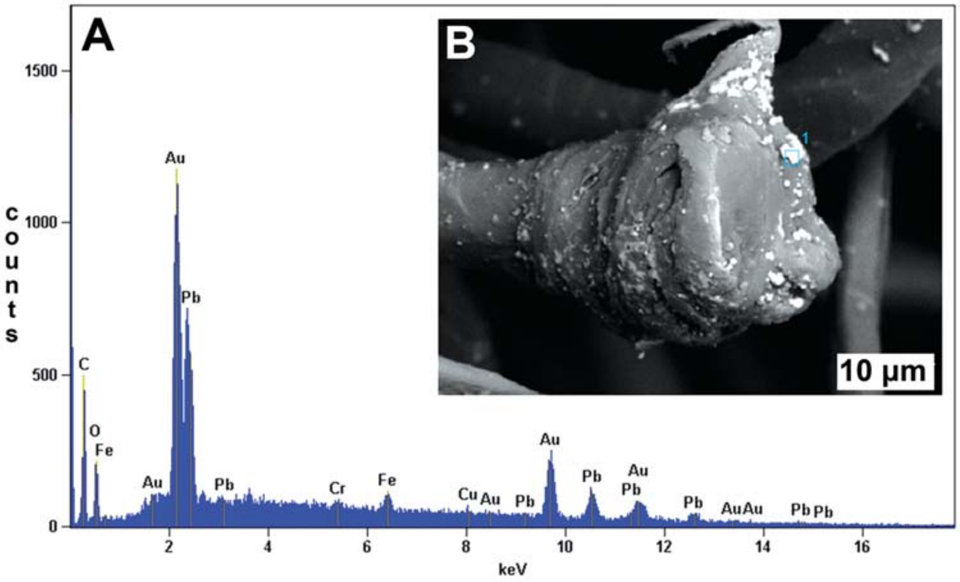

Figure 9. 9A: A BSE-SEM image shows the distribution of lead-rich particles on a broken polyester end. **9B:** EDS spectrum of one of these particles also shows the presence of iron and chromium, suggesting the presence of stainless steel. The gold peaks are a result of the coating applied to improve image resolution.

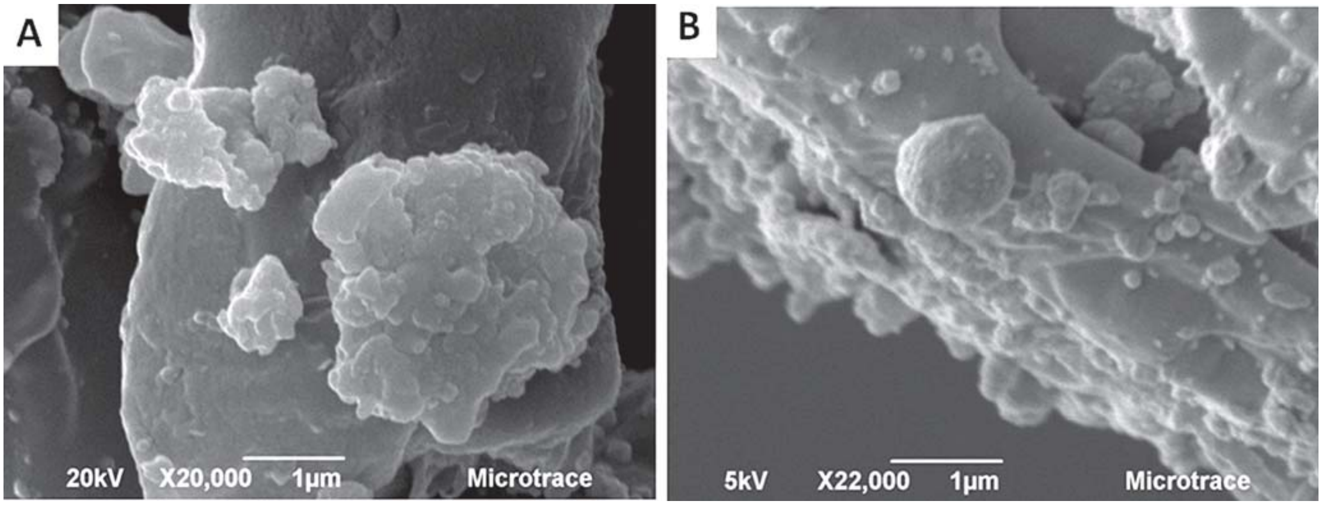

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Figure 10. SE-SEM images show **10A**, lead plates abraded from the perforating bullet and **10B**, a lead sphere resulting from aerosol deposition of molten lead. Both types of particles have similar elemental compositions.

Detailed examination of lead particles on these fiber surfaces show that most of them are platy or planar abrasion particles (Figure 10A), while occasional spherical particles are also observed (Figure 10B). Such spheres originate when molten lead cools and solidifies in air to a low surface energy (spherical) morphology. Both the spheres and plates have a similar elemental composition and are composed of lead, with minor antimony and copper (Figure 11). This composition is typical of a bullet lead alloy. None of the particles studied showed evidence of tri-component pGSR (Pb-Ba-Sb) particles (11).

The presence of fused fibers is shown at relatively low magnification in Figure 7A. The fusing of fibers, which was often observed among the fibers in each bullet hole studied, is shown in more detail in Figure 12. Detailed examination of these images shows two fused fibers at a variety of magnifications, which illustrate the extent of the fusing and the distribution of GSR particles on their surface. While lead particles are generally present in higher concentrations at the globular end of the fibers (and qualitatively decrease

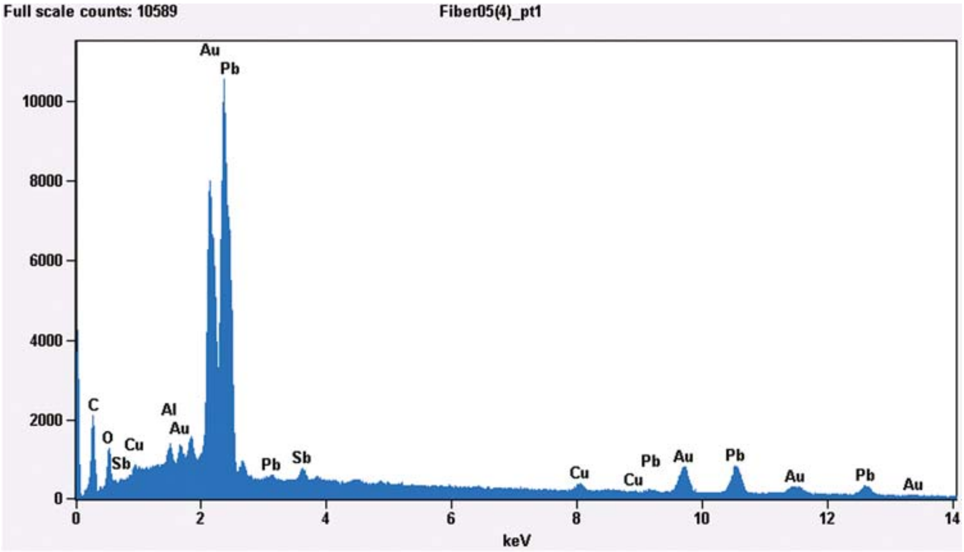

Figure 11. A typical EDS spectrum from a lead particle on the end of a severed fiber.

in number as the distance from the severed end increases), they are also present in high concentrations at the melted interface of the two fused fibers (Figure 12B and 12C). Examination of one of the fused areas also show that not only are the lead particles present on the surface of the fiber, but that they are also trapped within the fused areas, as confirmed by EDS and illustrated visually in the combined BSE/SE image shown in Figure 12D. These images illustrate the irrefutable link between a high-energy transfer and a lead-rich particle transfer, which can only originate from a ballistic event involving a lead or lead-laden projectile.

SUMMARY AND FORENSIC SIGNIFICANCE

These results indicate that a bullet hole from a jacketed soft point (exposed lead) bullet fired through a synthetic fabric can be definitively identified by studying the severed broken ends within a hole to identify the presence of globular ends and the presence of adhering and/or embedded lead particles.

Under certain circumstances, the issue may be raised as to whether certain variables may affect the formation or residence time (persistence) of the characteristic features noted above. Such variables may include environmental factors (such as weather), handling factors, fiber type, ammunition type, speed and firing distance.

Because the physical indicators of bullet perforation established above are subject to unknown and potentially disputed environmental variables (e.g. handling, washing, storage conditions and cross contamination) or firing variables (e.g. ammunition type and velocity), questions of persistence (i.e. residence time) will arise, particularly due to the similarities in particle size and composition shared by GSR. For example, a wealth of research into the affects of environmental conditions on the residence time of GSR particles has been conducted (11, 12) and many laboratories limit the collection of GSR to 24 hours or less after an incident due to concerns over residence and background contamination that may occur over longer periods (12). However, GSR is deposited by a distinctly different mechanism than metallic bullet fragments being transferred to severed fibers in a bullet hole. GSR is deposited *on* a surface at ambient conditions, while metallic ammunition particles transferred during partial melting of the fiber end are partially or entirely embedded *into* the fiber surface. This singular difference illustrates why metal particles associated with a bullet hole will have a distinctly longer residence time, regardless of handling conditions. Similarly, the characteristic globular ends are part of the fabric and are, therefore, not subject to any degradation beyond that expected for the garment as a whole. At ~20 µm in length, the globular end represents only a minor fraction of the total fiber length, which is generally at least 100x longer and physically anchored in the fabric. Therefore, both indicators of bullet perforation are expected to persist through harsh post-firing conditions.

While the exemplar in this work is composed of polyester fibers, many other types of fibers are used in the textile industry (e.g. nylon, polyolefin and rayon).

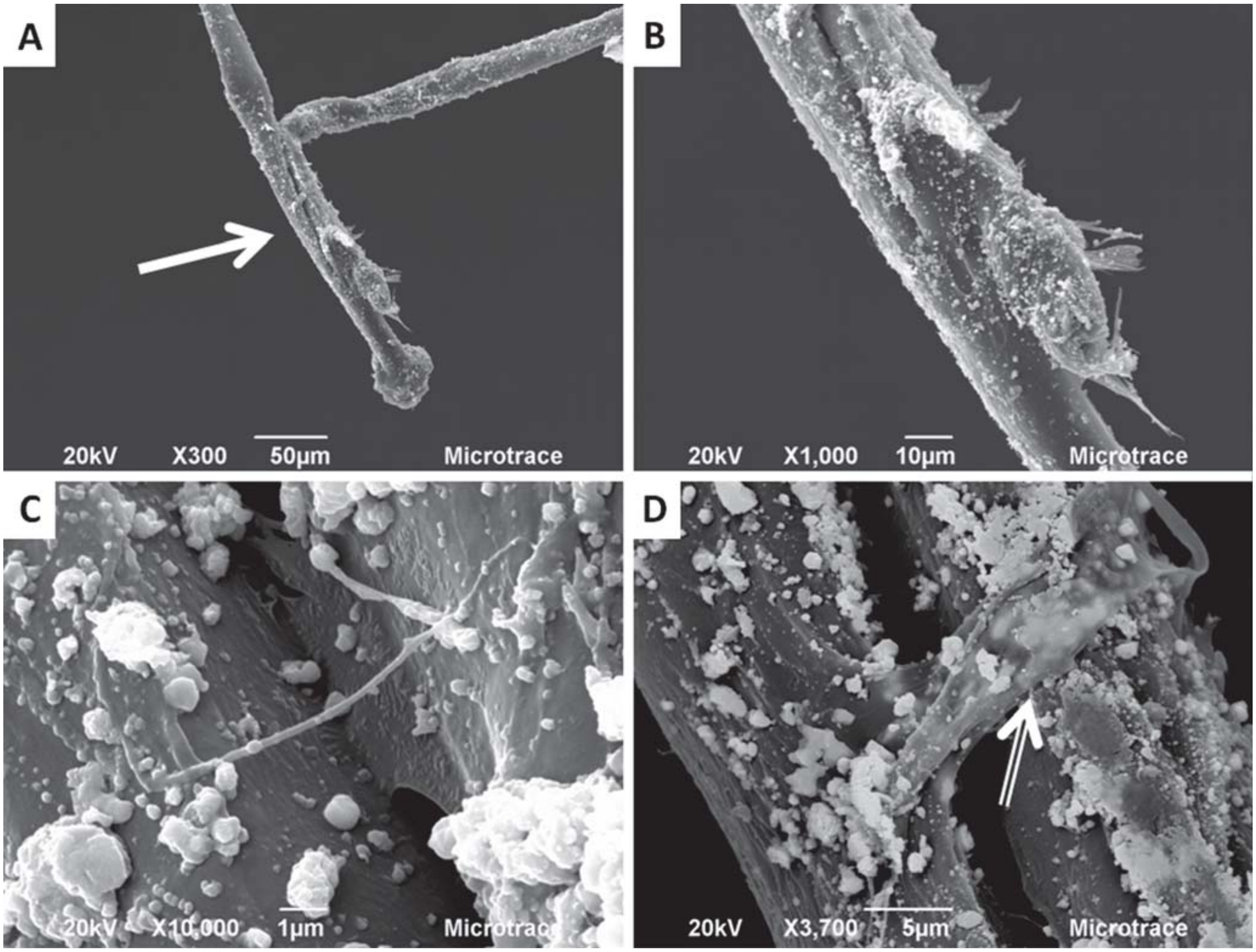

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Figure 12. **12A:** An SE-SEM image shows two fibers that were thermally fused during the high-speed impact event. **12B:** Close-up view of the area denoted by an arrow in part (12A) showing the presence of lead particles on the fused fibers (SE-SEM). **12C:** Highest magnification image of the same fused fibers at the melted interface showing individual, discrete lead particles abraded from the bullet during impact (SE-SEM). **12D:** Mixed SE-BSE SEM image shows that lead particles are actually embedded within the melted polymer (arrow).

The mechanism of high-energy tensile fracturing also occurs in other thermoplastic fibers such as nylon to produce similar globular ends (5). In contrast, cellulosic fibers (e.g. cotton, rayon and vegetable fibers) will not melt and, therefore, do not form globular ends. SEM examination of cotton fibers in our research confirms this (Figure 8), however, metal particles of lead were observed on the surface of the severed cotton fibers as well.

Ammunition type is another factor that will vary in casework. Ammunition and its jacketing are manufactured with various compositions. The detection of multiple metals on the globular ends by EDS in this work suggests that metals from bullets of different compositions and from different parts of the ammunition hold the potential to be transferred to a severed fiber. Conversely, the observation of specific lead alloys, GSR particles, copper, brass, stainless steel or other components can provide additional investigative information about the source of the impacting bullet.

Finally, the question of globular end formation may be challenged. The mechanism of globular end formation is directly related to the kinetic energy of the bullet passing through the fabric, which in turn is related to the velocity of the bullet. A prior study of globular ends produced in polyester and nylon fibers correlated to chronographed bullet velocities showed that various combinations of firearms and ammunition used to obtain velocities, ranging between 40 m/s and 823 m/s, all resulted in the production of globular ends (5). Microscopic features suggestive of other sources of fabric defect formation (e.g. "pinching" from scissors, tool marks from razor cuts, etc.) have also been studied (3) and have been shown to be different from those created by a bullet.

Therefore, in addition to proving a positive, the question may arise in certain contexts as to whether absence of such features can be used to state that a fabric "defect" was not produced by a bullet. Based on this research, both globular end formation and metallic particle capture would be expected to occur under all but the most extreme conditions. Therefore, it follows that the absence of such indicators is strongly suggestive of a negative conclusion — i.e. a bullet did not produce the hole.

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