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Detection of Bullet v. Nail Damage to Textile Fabrics Using Polarized Light Microscopy

ABSTRACT

This study compares natural and synthetic fabrics damaged by either a discharged bullet fired from a handgun or a nail ejected from a nail gun. Textile fabrics comprised of natural, synthetic, semi-synthetic, and blended fibers were damaged using five different handgun ammunition types. The fabrics were photographed using infrared photography and the fabrics damaged with a nail gun were chemically tested for copper and lead. Fibers were recovered from the damaged area, and the morphological and optical changes associated with the method of damage were examined.

Of the synthetic fabrics evaluated, only microfibers, nylon fibers and polyester fibers assume a mushroom-shaped morphology when damaged by a bullet. The undamaged region of the fibers display characteristic retardation colors under crossed polarizers, whereas the damaged area is isotropic. This phenomenon was also observed in a few nylon and microfibers damaged by a nail gun. The fibers removed from the vast majority of the nail gun holes did not display these characteristics. Further, all fabrics damaged with a nail gun gave negative results for copper. A very weak positive reaction with the sodium rhodizonate test occurred when the areas damaged by the nail gun were tested. The initial positive color results dissipated with the addition of 5% (v/v) HCl.

Keywords: Textile Fabrics, Ductile Fracture, Bullet and Nail Hole Damage, Fiber-end Deformation, Polarized Light Microscopy

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INTRODUCTION

The damage observed on textile fabric can provide useful forensic evidence with respect to reconstructing a criminal event, but determining the cause of the damage presents many challenges to a forensic examiner. One challenge to bullet damage analysis is the failure to detect GSR or bullet wipe on the damaged fabric. Studies show that fabrics exposed to various post-deposition factors (outdoor environments, blood, mechanical handling) for extended periods may potentially render false negative results, which presents a problem when relying on chemical testing to determine if the fabric was damaged by a firearm projectile [1-6].

Researchers have also focused on physical methods to identify bullet damage. Several studies have examined the morphology of fibers recovered from the margin of a bullet hole. Poole et al. [7] report that the ends of natural fibers displayed indistinguishable morphology regardless of whether the mechanism of damage was caused by stabbing or by a firearm projectile. The authors state that a mushroom morphology was sometimes observed at the ends of polyester fibers and consistently observed for nylon fibers when damaged by the firearm projectile. Haag also notes that nylon and polyester fibers removed from the bullet hole margin will display "swollen club-like ends" [1]. Carr et al. examined the damage caused to layers of 100% cotton clothing as well as the underlying tissue when impacted with a bullet [8]. They found that fibers associated with certain fabrics appeared cut or torn, whereas other fibers displayed a mushroom-like appearance. Palenik et al. report similar findings on examining individual fibers recovered from a bullet hole in a 70% cotton/30% polyester fabric blend. The authors report a "globular" end on polyester fibers but not on cotton fibers [9].

The goal of the study presented here was to compare a range of commonly encountered natural, semi-synthetic, and synthetic fabrics damaged by a fired bullet relative to a nail discharged from a nail gun. The textile fabrics examined include several fiber types that have not been previously reported in the literature. Specifically, the fibers were compared to determine whether it is possible to distinguish these two forms of damage. Given that GSR cannot always be detected near and around bullet holes, this study addresses the issue using a different approach by examining the morphological and optical changes associated with fibers damaged with each method. Further, the fabrics penetrated with a nail gun were subjected to dithiooxamide (DTO) and sodium rhodizonate chemical testing to determine whether chemical residues consistent with bullet wipe are associated with nail gun damage.

METHODS AND MATERIALS

Materials

Two data sets were prepared for this study. For data set one, 11 fabrics were selected as the target material, including 80% wool/20% nylon blend, 65% polyester/35% cotton blend, 100% polyester, 100% silk, 100% wool, 100% nylon, 6% spandex/94% cotton blend, 100% denim, microfiber (80% polyester/20% nylon blend), 100% Nomex®, and 100% Kevlar®. All fabric targets were mounted on cardboard backing and secured with duct tape. Three different ammunition types were selected for data set one: American Eagle 124 grain 9mm Luger full metal jacket (FMJ), American Eagle 230 grain 45 ACP FMJ, and Remington 115 grain 9mm Luger jacketed hollow point (JHP). Each ammunition was fired at each target in triplicate from either a 9mm Luger caliber Glock 17 or a 45 ACP caliber Colt 1911 semiautomatic pistol into each individual target at a distance of approximately six feet to the target. For comparison purposes, the individual fabrics from data set one were also penetrated using a 18V nail gun (Dewalt® Model DC618) loaded with 16 gauge nails with the magazine positioned at a 20° nail stick angle. No speed adjustment was available on the Dewalt® nail gun employed in this study and the specific speed of the nail on impacting the fabric was not determined. For data set two, 12 black-dyed fabrics were selected as the target material, including 100% wool, 65% polyester/35% cotton blend, 100% cotton, 100% polyester (spun), 100% acrylic (felt), 100% silk charmeuse, 100% nylon, 100% rayon, 100% polyester (fleece), 92% polyester/8% spandex blend, 90% nylon/10% spandex blend, and 100% olefin (polypropylene). For data set two, each fabric type was damaged individually, and seven sets of selected fabrics were also prepared as triplicate layers. The layers, listed in order of top, intermediate, and bottom layer were: wool, polyester (spun), cotton; wool, polyester (fleece), cotton; wool, olefin, cotton; nylon, acetate, polyester/cotton blend; nylon, rayon, polyester/cotton blend; silk, acrylic, polyester/spandex blend; and, silk, nylon, polyester/spandex blend. Two different ammunition types were selected for data set two: Winchester WinClean 115 grain 9mm Luger brass enclosed base (BEB), which incorporates a lead-free primer formulation and a brass alloy jacket, and Speer 115 grain 9mm Luger total metal jacket (TMJ). Each ammunition type was fired at each target in triplicate from a 9mm Luger caliber Glock 17 semiautomatic pistol into each individual target at a distance of approximately six feet to the target. For comparison purposes, the individual and triplicate layer fabrics from data set two were each also penetrated with a pneumatic framing nail gun (Hitachi, model # NR83A3) loaded with 0.313" gauge 21° angle nails and a pneumatic finishing nail gun (Senco, model # SFN30) loaded with 0.069" gauge finish nails. No speed adjustment was available on either the Hitachi or Senco nail guns employed in this study, and the specific speed of the nail on impacting the fabric was not determined.

Chemical Testing

The damaged area associated with each nail gun sample was initially observed under a stereomicroscope (Leica Microsystems Ltd, MEZ4D) at a magnification of X30 and photographed under tungsten and infrared illumination to observe chemical residues deposited on the fabric. The damaged area on the fabric was subsequently tested for the presence of copper residues (DTO reagent) [10] and for lead residues (sodium rhodizonate reagent) [11].

Observation of Morphological and Optical Properties

Fibers were removed from the damaged fabric and separated with forceps using stereomicroscopy (model EZ4D, Leica Microsystems Ltd). Microscopic examination included mounting the individual fibers on glass slides (Plain Beveled Edge, Pre-cleaned, 72mm x 25mm, Approx. 1mm thick, Premiere®, VWR) with glass coverslips (22x50mm No. 2 or 24mm x 50mm No. 1, VWR®) in CytosealTM 60 mounting medium (RI=1.48, Richard-Allan Scientific). The fibers were viewed under both plane polarized transmitted light and crossed polarizers (DMPL model with attached 450 camera system, Leica Microsystems Ltd,) at 100 times magnification to examine the morphological and optical properties associated with the damaged fiber ends.

RESULTS AND DISCUSSION

Preliminary chemical tests were performed on the nail gun samples to replicate the typical procedure followed by a forensic examiner to determine whether fabric damage is possibly attributed to a fired bullet.

Preliminary Morphological Examination and Chemical Testing for Data Set One

One source of evidence that may indicate whether a target was damaged by a bullet is the presence of bullet wipe residue (12, 13) in the area immediately surrounding the bullet hole. Bullet wipe typically consists of chemical elements associated with the bullet, including the core and jacket, lubricant, burnt and unburnt propellant, and primer residue. Of note, no bullet wipe was observed around the damaged areas associated with any of the fabrics penetrated with a nail gun. Further, all of the fabrics damaged with a nail gun gave negative results for copper and most gave negative results for lead; however, there was a very weak positive reaction with the sodium rhodizonate test when the areas damaged by the nail gun were tested. The initial positive color results disappeared with the addition of 5% (v/v) HCl. This step causes the purple color reaction to dissipate for non-lead sources, such as strontium and barium, whereas the color persists when reacting with lead.

Preliminary Morphological Examination and Chemical Testing for Data Set Two

The holes formed in the fabrics damaged by the pneumatic nail guns exhibited an impression that was light gray in color. The hole formed by a finishing nail was smaller in size compared with the hole caused by a framing nail. As such, the framing nail damage was more apparent and easier to detect. For the triplicate layer sample sets, the damaged area of the hole was extremely frayed in both the top and intermediate layers. Preliminary chemical tests for the residue associated with both the framing and finishing nail guns showed negative results with the DTO and sodium rhodizonate reagents.

Damage in Natural vs Synthetic Fibers

The natural fibers damaged with either a bullet or nail showed no change in their morphological and optical properties other than displaying a slightly irregular torn end. The optical properties of the natural fibers were unchanged as a result of bullet or nail impact in that they displayed birefringence across the entire length of the fiber. Cotton fibers are primarily composed of cellulose, which burns but does not melt when heat is applied. Likewise, silk and wool are protein-based fibers composed of fibroin and keratin, respectively [14], both of which also do not melt. Some synthetic and semi-synthetic fibers (spandex, rayon, olefin [polypropylene], and acrylic) also displayed a torn appearance. In contrast, the damaged ends of other synthetic fibers, such as Nomex® and Kevlar®, displayed a more rounded appearance that also retained birefringent properties.

In comparison with natural fibers, nylon, microfiber, and polyester fibers damaged with a bullet displayed the greatest difference in both morphology and optical properties in the damaged fiber ends (Figure 1B,D,E,F). These three fabrics exhibited numerous fibers with a characteristic mushroom-shaped end that exhibit zero retardation (isotropic) when viewed under crossed polarizers, as previously described for polyester and nylon [1,7-9,15-16]. A sampling of several fields of view showed that approximately 85% of polyester fibers, and approximately 90% of nylon fibers and microfibers display a characteristic mushroom-shaped end that exhibit zero retardation. These results were consistent for each triplicate sampling for the nylon, polyester, and microfiber fabrics regardless of the ammunition/firearm combination. The results also held true for the polyester and nylon components of the blended fabrics. Further, comparable morphology and optical properties were observed for the polyester and nylon fibers recovered from the single and triplicate layer samples.

There was also evidence that a few isolated nylon fibers and microfibers damaged with a nail gun exhibit the characteristic mushroom-shaped end that was isotropic when viewed under crossed polarizers (Figure 1A,C). The DeWalt, Senco and Hitachi nail guns employed in this study are combustion nailers. The nail gun combustion chamber contains flammable gas that mixes with air and ignites when exposed to sparks generated from a spark plug. The pressure generated from this explosion projects the nail from the nail gun. Therefore, it is reasonable to hypothesize that heat will be transferred to the nail during the combustion process. However, only a few isolated examples of fibers displaying these mushroom-shaped end characteristics were observed in association with the nail gun damage; fibers removed from the vast majority of the nail gun holes did not display these characteristics. A sampling of several fields of view showed that approximately 2-4% of nylon fibers and microfibers display a characteristic mushroom-shaped end that exhibit zero retardation. While fewer than 1% of the polyester fibers damaged by the nail gun appear to be forming a mushroom-shaped morphology, there is no obvious isotropy associated with the damaged area. Fewer than 1% of the polyester fibers do show isotropy but the mushroom-shaped morphology is not apparent for these fibers. Its possible that these particular fibers have been stretched, thus reducing the fiber diameter (Figure 2A,B,C).

One potential theory accounting for the lower numbers with a nailgun relative to a bullet may be the amount of heat transferred to the nail and/or the distribution of heat along the length of the nail. Another potential contributing factor may be the reduced contact that occurs between the nail and the surface area of the fabric relative to a bullet, given the narrower diameter of the nail.

Polyester and nylon burn and melt when exposed to heat. However, while mushroom-shaped fiber ends damaged by a bullet were common in nylon, they were absent in other synthetic polyamide fibers, including Nomex® and Kevlar® for which there was no evidence of isotropy at the damaged end. The lack of mushroom-shaped ends in Kevlar® and Nomex® may be attributed to the molecular structure of the fibers. Both of these materials consist of aromatic rings linkages, which impart significantly greater tensile strength to the fibers relative to the aliphatic carbon chains that comprise the polymer structure of nylon fibers [17, 18]. Kevlar® and Nomex® differ in the phenyl group linkage orientation; Kevlar® is para-substituted, whereas Nomex® is meta-substituted. In the case of Kevlar®, para-substitution of aromatic groups to the carbonyl and NH functional groups within the polymer chain confers considerable rigidity to the fibers [17]. While meta-substitution reduces the rigidity of the Nomex® polymer chain, this linkage imparts superior thermal resistivity and very poor heat conductivity [18]. Given these properties, neither Kevlar® nor Nomex® fibers melt when heated, which explains the lack of a mushroom-shaped end when impacted with either a bullet or a nail. The bullet and nail-damaged fibers associated with olefin (polypropylene), rayon, and acrylic also lacked a mushroom-shaped end; rather, the damaged ends exhibited a torn edge for each of these fabrics. The absence of a mushroom-shaped end for rayon and acrylic is explained by the fact that they burn but are both non-melting fibers. However, this does not explain the results obtained for olefin (polypropylene), which does melt, typically at a relatively lower temperature (120-168 °C) compared with nylon and polyester.

The bullet and nail-damaged fiber ends in spandex displayed a relatively smooth edge with no evidence of isotropy at the damaged end (Figure 1G, H). In theory, the lack of mushroom-shaped ends may be related to the lower tensile strength of spandex fibers compared with other synthetic fibers. While the elasticity of spandex allows for high breaking elongation, it exhibits a low modulus of elasticity and is less resistant to stress. As a result, spandex fibers have a relatively lower breaking tenacity (0.6-0.9 g/d) compared with nylon (7.5-10.5 g/d) and polyester (7.0-10.0 g/d) fibers [19]. Accordingly, despite the fact that spandex does typically melt at 230°C, it is plausible to hypothesize that the force associated with a bullet or nail may be breaking the fiber apart more rapidly without transferring sufficient heat to the breakage location.

In summary, the results obtained are consistent with the concept that the high-energy impact associated with either a bullet, and to a far lesser degree with a nail deployed by a nail gun promotes melting at the breakage region of the fiber and causes the terminal ends of the heated polymer to expand [15]. Hearle at al. explain that high-speed fractures occur under adiabatic conditions, whereby the heat associated with fiber extension warms the fiber at the point of fracture rather than being lost to the immediate environment (as is the case with isothermal conditions associated with low speed fractures). The authors propose that softening promotes the flow of viscous materials that is confined to the breakage region of the fiber, and, following separation, the terminal ends of the heated polymer expand [15]. Haward also reports that for fast deformation under adiabatic conditions, the softening effect exceeds the opposing stain hardening, leading to a ductile fracture that may display mushroom-shaped ends [16]. This localized heating will presumably disrupt the symmetry of the monomers associated with the synthetic fibers. Given that the bullet or nail is affecting the polymeric structure of the synthetic fibers, this is expected to impact the uniform alignment of the polymer molecules and alter the optical properties of the fiber.

The velocity and associated heat transfer to the nail following deployment by a nail gun was not determined in the research reported here but is a recommended future study in order to compare with bullet velocities provided by the ammunition manufacturer. Another experiment to consider is setting up a close range muzzle-to-target distance for the olefin and spandex fabric, exposing these fabrics to muzzle flash to determine whether melting occurs at the ends of the damaged fibers.

CONCLUSIONS

The microscopy results show that the damage caused to fibers by the penetration of a discharged bullet or a nail deployed from a nail gun is indistinguishable when penetrating silk, cotton, wool, Nomex®, Kevlar®, rayon, acrylic, olefin (polypropylene), or spandex. In each case, the damaged end of the fiber resembles a slightly irregular torn morphology. In contrast, when a bullet penetrated nylon or microfiber fabric, approximately 85-90% of fibers displayed a mushroom-shaped morphology that were also isotropic when viewed under crossed polarizers. However, only approximately 2-4% of fibers displaying mushroom-shaped ends were observed associated with the nail gun damage; fibers removed from the vast majority of the nail gun holes did not display these characteristics.

Further, there was no clear evidence of polyester fibers displaying isotropic mushroom-shaped ends when damaged with a nail gun.

The mushroom-shaped morphology and resultant modifications to the optical properties of a damaged fiber indicate a high-speed fracture, which includes a bullet discharged from a firearm or, albeit to a far lesser degree, a nail deployed from a nail gun. These observations are limited to fibers that exhibit melting properties. Further, this study shows that the absence of mushroom-shaped fibers surrounding bullet holes in spandex and olefin (polypropylene) supports that the melting property of a fiber does not fully account for the formation of expanded terminal ends when impacted by a bullet or a nail.

Similar results to those reported here may be observed with other forms of high-energy impact that are sufficient to deform the molecular structure of a polymer. For example, one study demonstrated the formation of a mushroom-like ball at the end of nylon fibers when automobile seat belt webbing separates under tension due to a collision [20]. Other potential examples include shrapnel or other fragments that are projected as a result of an explosion or the torn edges of automobile airbag fabric following deployment.

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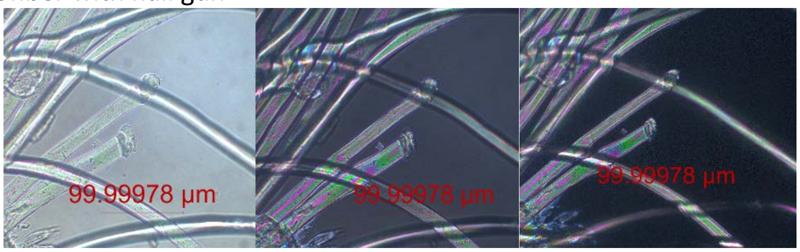
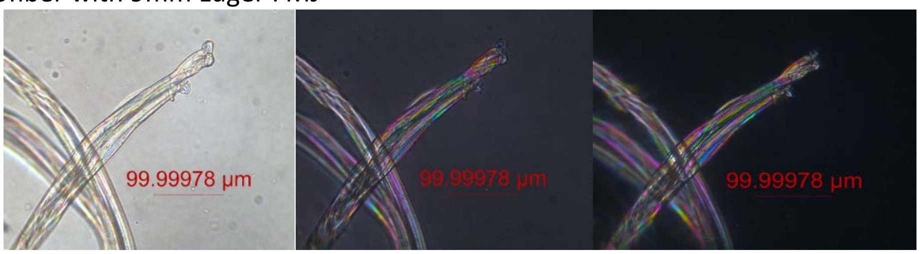
Figure 1: Synthetic fibers damaged with a bullet and nail gun viewed under plane polarized light (left), 65° crossed polarizers (middle) and 90° crossed polarizers (right). Magnification x400.

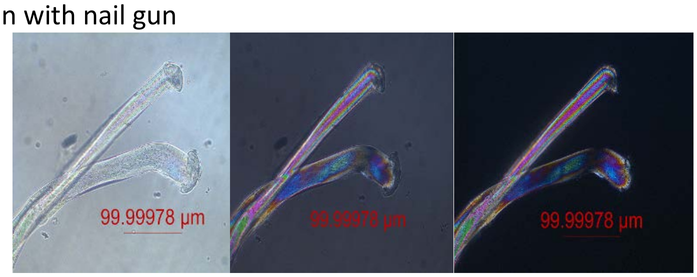
A: Microfiber with nail gun



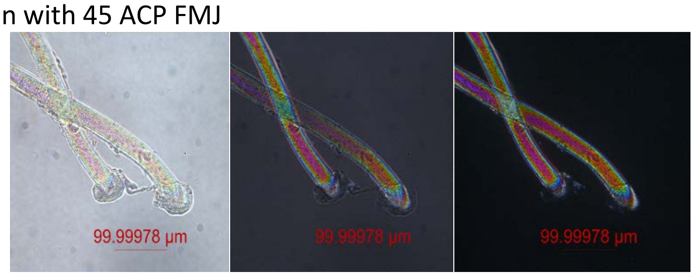
B: Microfiber with 9mm Luger FMJ



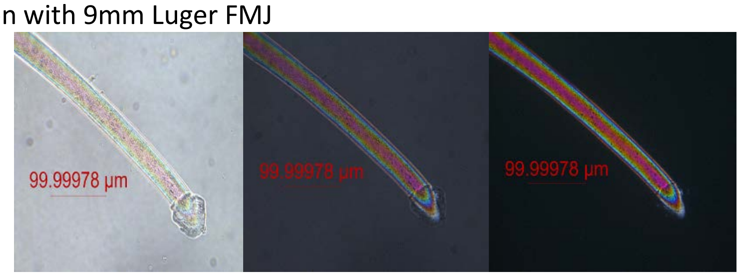
C: Nylon with nail gun



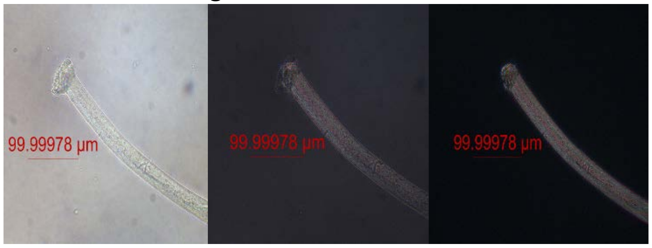
D: Nylon with 45 ACP FMJ



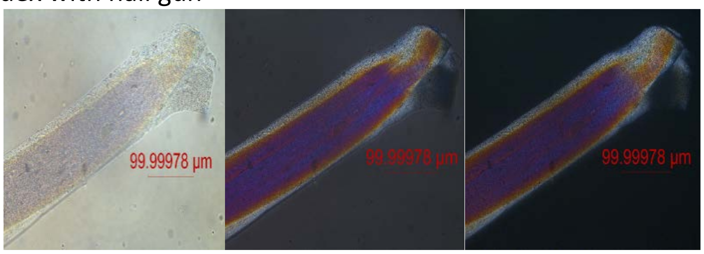
E: Nylon with 9mm Luger FMJ



F: Polyester with 9mm Luger BEB



G: Spandex with nail gun



H: Spandex with 9mm Luger JHP

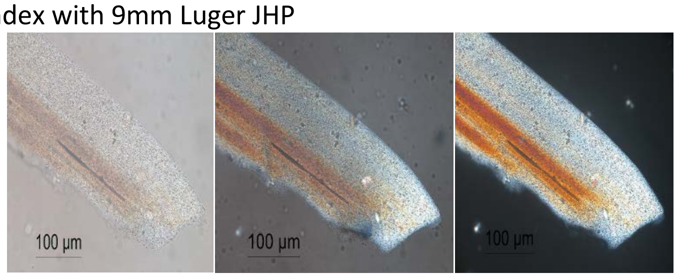
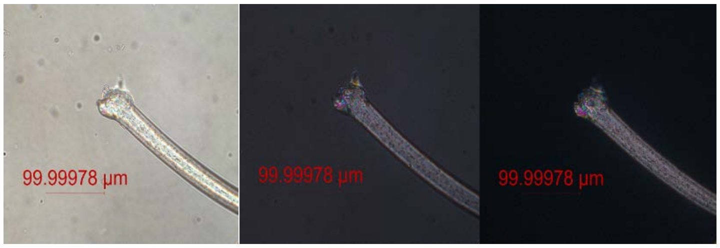
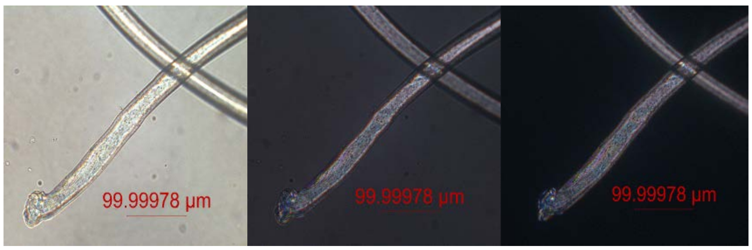


Figure 2: Polyester fibers damaged with a nail gun viewed under plane polarized light (left), 65° crossed polarizers (middle) and 90° crossed polarizers (right). Magnification x400.

A: Sample 1



B: Sample 2



C: Sample 3