Environmental Factors Affecting Rapid Shear in Fibers from the Passage of a Bullet

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Environmental Factors Affecting Rapid Shear in Fibers from the Passage of a Bullet

A Thesis Presented in Partial Fulfillment of the Requirements for the Degree of

Master of Science in Forensic Science

John Jay College of Criminal Justice

The City University of New York

Laura Molina

August 2018
Environmental Factors Affecting Rapid Shear in Fibers from the Passage of a Bullet

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This thesis has been presented to and accepted by the office of Graduate Studies, John Jay College of Criminal Justice in partial fulfillment of the requirements for the degree of Master of Science in Forensic Science.

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# Table of Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acknowledgments</td>
<td>i</td>
</tr>
<tr>
<td>Abstract</td>
<td>ii</td>
</tr>
<tr>
<td>Introduction</td>
<td>1 – 9</td>
</tr>
<tr>
<td>Methods and Materials</td>
<td>9 – 17</td>
</tr>
<tr>
<td>Results</td>
<td>18 – 26</td>
</tr>
<tr>
<td>Discussion</td>
<td>27 – 28</td>
</tr>
<tr>
<td>References</td>
<td>29 – 30</td>
</tr>
<tr>
<td>Appendix</td>
<td>31</td>
</tr>
</tbody>
</table>
Acknowledgements

This research would not have been possible without the dedicated forensic science professors on my thesis committee. Dr. Peter Diaczuk was graciously willing to explain and provide guidance, with a great amount of patience along the way. Dr. John Reffner provided his time to teach complex microscopy concepts and ensure my understanding of them. Dr. Nicholas Petraco was always willing to help even at a short moment’s notice.

I am also very grateful to every person I encountered who showed an interest in my research and allowed me to discuss ideas or resolutions to problems along the way. I feel very privileged to have been able to conduct work in an area in which I had minimal background experience. Thank you to my family and friends for lending their support through my graduate studies journey.
Abstract

Evaluation of fabric defects may provide insight on the specific cause of fiber fracture. In forensic casework, fabric defects may provide a determination of previous occurrences connected to a case. Different methods of fabric breakage impart differing physical characteristics on individual fibers. These alterations to otherwise highly ordered fibers are determined by a multitude of factors, among them temperature. The process of rapid shear occurs in thermoplastic materials following high-speed impact. It results in distinct features caused by excessive heat generated through the interaction which is unable to dissipate at a rate that would leave the fibers unchanged. Rapid shear characteristics can be differentiated from other fracture patterns through non-destructive microscopical methods and with a minimal sample size.

Due to the importance of temperature in the rapid shear process, temperature altering environmental factors could affect observable fiber characteristics after projectile-fabric interaction. This study aimed to discern how environmental conditions could influence those detectable features. Fabric samples were shot under heated, chilled, and water-saturated conditions, using ammunition of varying velocities. Analyses performed on the defects were conducted using stereomicroscopy, polarized light microscopy and scanning electron microscopy. Globular-shaped fiber ends, characteristics attributed specifically to rapid shear, were observed in all nylon sample types through the microscopical methods noted. Furthermore, loss of birefringence and changes in retardation were noted in these fibers under crossed polarized light. Through this study, it was discovered that the environmental conditions employed did not affect fiber end changes associated with rapid shear.
Introduction

An individual’s presence at a crime scene in which bullets were fired may be displayed in an obvious manner such as by either a resultant bullet wound, bullet fragments, or the remnants of bullet wipe and gunshot residue. However, at times a forensic analyst may be faced with determining an individual’s or an object’s connection to a crime scene with only a fabric defect to evaluate. While propellant particles embedded in the fabric may provide useful information in close-range shootings, another way to approach such an investigation could be by analysis of individual fiber ends around the bullet impact site. These investigative methods are non-destructive and may be carried out with a limited sample size, both of which are vital for forensic analysis.

Fiber damage or fracture can be caused by a multitude of reasons: burning, cutting, tearing, wearing and piercing of projectiles, amongst others. Each of these actions can impart its own distinct characteristic on impacted fibers, specifically at the margin of a fabric defect. Normally, when a fiber is damaged it stretches before breakage, which allows heat to dissipate (Huemmer, 2007). Rapid shear is a phenomenon observed in thermoplastic materials following the puncturing of a projectile during which the circumstances differ (Huemmer, 2007). The mechanical categorization of this fabric failure type is as high-speed tensile break (Hearle, Lomas, & Cooke, 1998). This interaction between bullet and fabric involves the combination of increased kinetic energy with a small site of perforation, which set the conditions for the mechanism to ensue (Haag & Haag, 2011).

Fiber fracture occurs in rapid shear cases but unlike typical damage, the heat is unable to dissipate slowly, thereby causing the formation of specifically altered fiber ends (Hearle et al., 1998). Although the fabric and projectile experience a brief interaction, the projectile’s crushing
power alters the fibers as it forces its way past them (Haag, 2005). This damage to individual fibers, and therefore indicators of the rapid shear process, are best distinguished from other types of fabric damage using microscopical analysis. Microscopically, it is identifiable through the display of melted, globular fiber ends in the perimeter of the tear (Haag & Haag, 2011). The cause of these changes to fiber features was believed to be the heat of the projectile, or heat caused by friction at impact (Haag, 2005). Then, through further investigations, it was also hypothesized to be a result of heat transfer due to the high bullet velocity (Haag, 2005).

According to the most recent theory, the generation of heat due to the stretching and tearing of the polymer chain internally is the most significant factor. Additionally, investigations have shown loss of birefringence upon globular end formation with fibers previously evaluated as highly birefringent (Haag & Haag, 2011). This alteration to optical properties requires a more in depth analysis and comparison of the fibers of interest. However, it helps in confirming the occurrence of rapid shear, especially when coupled with the verification of physical changes.

Research has revealed several factors to be responsible for the exhibition of this mechanism. Ammunition composition and shape, gun type, fabric composition and backing (or shoring), bullet velocity, firing distance, and handling methods are all variables which should be taken into account with formation of characteristic fiber ends (Palenik, Palenik, & Diaczuk, 2013). Another aspect of rapid shear formation which has not been evaluated is how these alterations could be influenced by external variables, such as environmental changes and fabric temperature upon impact. Due to the significance of all the factors acting jointly on the fibers, differences in the final facets may be noted. Further, this process is a temperature dependent one, which can be affected or impeded by the changing external conditions and fabric temperature.
Therefore, studying these variables may reveal whether temperature change past a certain threshold may affect the other factors and consequently the mechanism as a whole.

**Literature Review**

Palenik, Palenik, and Diaczuk (2013) combined fiber end analysis with lead particle identification to convincingly determine bullet perforation in fabric. In this study, the fiber ends of polyester fabric samples impacted by jacketed soft point bullets were analyzed by stereomicroscopy, polarized light microscopy, and scanning electron microscopy. An AK-47 rifle was used to fire and create exemplar garment holes on fabric composed of 70% cotton and 30% polyester. Severed polyester fibers revealed melted, bulbous shaped ends which could be detected even at low magnifications on a stereomicroscope. Furthermore, this specific fiber end morphology was confirmed through polarized light and scanning electron microscopy. Positive lead particle detection was completed through backscattered electron (BSE) imaging as well as energy-dispersive X-ray spectroscopy (EDS). The transfer of lead particles from the firearm and ammunition to the fiber was expected to take place at the interaction of bullet and fiber, in the similar time window as fiber alterations occur. The researchers stated that based on these results, absence of globular fiber ends and lead particle capture could in fact be indicative of a negative condition, or no bullet perforation.

Moreover, in “Plumbum Microraptus” the bullet-synthetic fabric interaction is explained by being broken down into a minimum of two transfer phases. One being energy transfer that leads to fiber breakage while the second involves material transfer, whereby bullet particles or material can be deposited onto the fractured fiber ends or conversely, polymer may be transferred onto the bullet. The researchers also stated that kinetic energy displacement from projectile to fibers is responsible for inducing the tension which is then followed by fiber
breakage. This adequate energy transfer produces the melting of thermoplastic polymers making up the fibers. However, this result is not detectable in fiber types which do not exhibit melting but rather those fabric types containing certain, though not all, synthetics. Authors of this paper mentioned the fusing of fibers as an indicator of increased temperature and fiber modification. In addition to the fusing identified under microscopical analysis, other visible signs of mechanism failure were said to be the melting and recoiling of fibers following the stretching, also known as “globular” end characteristics. Fiber end characteristics from this process are a lasting part of the fibers, but cover a minimal amount of surface area when compared to the fiber length as a whole.

These morphological, as well as, optical features of the rapid shear process, can be detected via microscopical analysis. Through the irreversible fiber changes taking place in this process, orientation loss occurs as the melting and cooling phases proceed without order. From the results obtained in the Palenik et al. experiment, a point was made that multiple factors may influence the creation of these fiber alterations in addition to the length of time they may be expected to persist after bullet perforation.

Craig L. Huemmer (2007) conducted a study to better examine the multiple variables that play part in the rapid shear process. By analyzing impact velocities, bullet shape, fabric shoring, type, and composition, in addition to fiber type, a speed threshold for specific variable combinations could possibly be discerned. In this investigation, mounted nylon and polyester fabric samples of the same size were shot with revolvers, a semi-automatic rifle, and an air rifle. The construction and backing of these samples were different throughout. Fabric samples differed between woven and knitted, as well as shored or un-shored. The construction and composition of fabric influences physical and mechanical properties of the fibers themselves (Huemmer, 2007). It was hypothesized that knitted fabric and unshored samples, with no backing
or support present, would allow more stress from bullet impact to be relieved and thereby create less extreme alterations to the fiber ends.

Ammunition type varied in Huemmer's study, bullet ogive shapes were contrasted through the use of round nose and wadcutter bullets. Firearms and air rifles were categorized as high and low velocity impact respectively, with a median velocity obtained by revolvers. Different velocities were also used through altering powder loading from the original amount to about 90% and 75%. Additional velocity reduction was obtained by reloading only 60-10% of the original load and completely removing all powder. Shooting occurred in a perpendicular direction to fabric mounting.

Analysis included stereomicroscope and polarized light microscope (PLM) observations in addition to comparison of other fiber damage methods. Other fracture patterns were gathered through the researcher’s manipulation of various pointed objects. Melting temperature analysis was conducted through the use of a polarized light microscope and a Mettler hot-stage. All samples revealed the distinct fiber ends associated with rapid shear. The fiber ends took on globular or melted characteristics and a change in retardation from undamaged to damaged fiber areas was observed. Fibers cut by other means besides shooting were not noted to display these specific characteristics.

Steven G. Wintonick (2002) conducted research which focused on the use of a scanning electron microscope, or SEM, as a means for analyzing textile evidence. This microscopic method was reviewed as SEMs exceed other forms of analysis in resolution, magnification, and depth of field- which could provide a more consistent and accurate testing of the fibers in question. The study was carried out through the different rupture of cotton fibers constituting denim samples. The two categories of fiber fracture evaluated were cutting and tearing, both
common fiber alterations. Cutting by scissors, razors, and knives were compared among themselves in addition to bullet perforations in this experiment.

The purpose of Wintonick’s comparisons were to possibly identify any morphological differences or variations evident between fracture methods. It was important to produce cuts or tears in the samples in a reproducible manner. Stereomicroscopes were used when removing impacted fibers and preparing visualization of the changed ends. Additionally, before microscopical examination, a carbon coating was applied to the samples to improve the images obtained and counter any effects caused by charging or beam damage. Coating was conducted at an optimal thickness believed not to cause any masking of fiber features. Appropriate SEM operating conditions and settings were decided through multiple trials of sample viewing. All samples showed slight similarities in their damaged fiber end characteristics but also revealed distinct facets unique to the specific fracture method. This research emphasized the importance of scanning electron microscopy analysis on fiber fracture characteristics in addition to the unique details imparted on fibers based on fracture method. It also aided in establishing a protocol for this method of analysis.

**Experimental Design**

Rapid shear studies in the past have aimed at better understanding the aspects of the phenomenon at the fabric-projectile interaction point. While various factors have been noted to influence this process, minimal attention has been directed to more external or environmental variables. In order to rely on the identification of this specific fiber alteration, with regards to forensic cases, it is necessary to comprehend the dynamic of this process under different extrinsic conditions. Crimes can occur under a variety of external circumstances which were
attempted to be replicated in this study through fabric sample manipulations. Those conditions included extreme heat and cold, as well as the water-soaking of samples.

Upon completion of fabric sample preparation, a variety of firearms and ammunition were employed in the creation of exemplar defects. As projectile velocity has been noted to be a significant factor in this process, it was varied throughout the samples. Specifically, lower velocities were chosen in order to potentially observe a minimal threshold for this process. From there, samples were carefully separated and stored in order to accurately keep track of the conditions for each. The microscopical methods chosen for this particular study were selected based on previous studies such as those cited in the literature review. They were used in order from lower to higher magnification ranges, as were needed for an increasingly in-depth analysis of the fabric samples.

**Stereomicroscopy**

A stereomicroscope is a type of compound microscope characterized by two spatially distinct optical paths through separate objectives and eyepieces (Ruzin, 2017). This specialized microscope provides the viewer with a three dimensional image, which is obtained as a result of difference in angles from one light path to the other providing two slightly differing images of the sample (Ruzin, 2017). The imaging presented by stereomicroscopy is formed through the normal function of the human brain and eyes (Nothnagle, Chambers, & Davidson, n.d.). This microscopical analysis works through the use of both transmitted and reflected illumination, although more commonly reflected lighting (Nothnagle, Chambers, Parry-Hill, Fellers, & Davidson, 2015). While a stereomicroscope may not provide high levels of magnification, it does provide a spacious field and substantial working distance (Nothnagle et al., n.d.)
**Polarized light Microscopy**

A polarized light microscope is typically used for the study of optically anisotropic samples and can function as a qualitative or quantitative form of analysis. This microscope contains two polarizers, one termed a polarizer and the other an analyzer, placed in different location with regards to the sample/specimen. The polarizer is found before the sample in the path of light while the analyzer is placed between observation tubes and the objective rear aperture in the optical path (Robinson & Davidson, n.d.). This setup provides contrast due to plane-polarized light interacting with the birefringent sample and producing separate wave components which are both perpendicularly polarized in regards to the other (Robinson & Davidson, n.d.). The purpose of the analyzer is to aid in the recombination of the light components once they leave the sample and are out of phase, through constructive and destructive interference (Robinson & Davidson, n.d.). Additionally, retardation plates of different wavelengths can be used for the estimation of optical path variations (Davidson, n.d.).

**Scanning Electron Microscopy**

A scanning electron microscope functions through the bombardment of electrons onto the sample surface. A stage within the chamber houses the sample, while an electron optical column with lenses placed directly above the sample aids in the focusing of electrons to a specific location on the surface of the specimen (“An Introduction to Electron Microscopy”, n.d.). Scan coils over the objective lens work to control the electron beam position (“How an SEM Works”, n.d.). Different signal intensities are then measured by a secondary electron or backscatter detector when the electron beam and sample interact (“An Introduction to Electron Microscopy”, n.d.). The detected signals can evaluate specimen morphology, chemical configuration, as well
as crystalline orientation or structure (Swapp, n.d.). The magnification capacity of an SEM is much greater but may be limited by sample preparation and other factors.

**Methods and Materials**

**Fabric Samples**

The focus of this study was on nylon, a synthetic and thermoplastic fabric, which had been previously determined as exhibiting rapid shear characteristics (Huemmer, 2007). This fabric type was chosen in order to alter some of the other factors involved in the process, with the certainty that the specific fiber alterations would appear under favorable conditions. Two types of nylon fabric samples were purchased through Testfabrics, Inc., filament nylon 6.6 semi-dull taffeta, scoured, heat set and texturized nylon 6.6 stretch fabric, double knit. Samples were cut into squares of approximately ten inches by ten inches and kept separated based on nylon type. Figures 1 and 2 depict close up images of the Nylon sample compositions used in this study.

*Figure 1. Nylon 6.6 semi-dull taffeta, scoured heat set fabric sample.*
Texturized Nylon 6.6 stretch fabric, double knit fabric sample.

**Fabric Mounting.** Sample mounting varied by whether the shooting was conducted indoors or outdoors and in some instances by the type of firearm or set up necessary. The first outdoor shooting, by semi-automatic pistols, involved samples clamped at each corner onto a cardboard backing. While the samples here were stretched out, they were not rigid. The outdoor air rifle samples had to be mounted in a taut position in order for the air rifle projectiles to fully perforate the fabric. These samples were shot under shored, pinned to a plastic backing, and unshored, clamped at each corner to a plastic frame, conditions. The indoor samples were unshored during all shooting by the pistol and semi-automatic rifles but were instead clamped on the two top corners to a wooden frame. Fabric mounting was conducted so as to proceed with shooting perpendicularly to the samples.
Sample Firing

**Firing Velocity.** Different firearms and ammunition of varying velocities were used in order to assess the affects of velocity changes to the process along with environmental alterations. Figure 3 below displays a majority of the cartridge categories used in the creation of exemplar fabric defects.

*Figure 3.* Representation of the four main cartridge types used in this research, from left to right: .22LR, .32ACP, 9mmL, 7.62 x 39mm.

In some instances, a firearm with multiple ammunition types provided a smaller velocity window than changes in velocities from one firearm to another. The higher velocity ranges were provided with the AK-47, Ruger 10/22, and Glock 19. While the Walther PPK and GSG-1911-22
constituted the firearms providing medium velocities. And the M417 air rifle comprised the lowest velocity employed in this study. Table 1 displays the firearms and their respective velocities from lowest to highest, based on the ammunition type used.

**Table 1**

*Firearm Velocity Ranges*

<table>
<thead>
<tr>
<th>Firearm</th>
<th>Caliber</th>
<th>Velocity Range (feet per second)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M417 Air Rifle</td>
<td>.177</td>
<td>459</td>
</tr>
<tr>
<td>GSG-1911-22</td>
<td>22LR</td>
<td>710</td>
</tr>
<tr>
<td>Walther PPK</td>
<td>.32 ACP</td>
<td>900</td>
</tr>
<tr>
<td>Glock 19</td>
<td>9mmL</td>
<td>1225-1250; 1100</td>
</tr>
<tr>
<td>Ruger 10/22</td>
<td>22LR</td>
<td>1235</td>
</tr>
<tr>
<td>AK-47</td>
<td>7.62 x 39mm</td>
<td>2300</td>
</tr>
</tbody>
</table>

**Firing Distance.** In most circumstances, the shooting distance was dictated by the sample and firearm setup. The exemplar shooting was conducted at a distance of approximately three to eight feet. All outdoor samples were prepared from an eight-foot distance except for the air rifle samples which were created from a three-foot distance. This shorter distance was again due to difficulty ensuring complete projectile perforation with air rifle samples. All indoor samples were prepared from a distance of three feet.

**Firing Replicates.** Every set of conditions consisted of the firing on both fabric sample types, approximately three samples for each set. Furthermore, each fabric sample was shot multiple times, between 3 and 12 times. The firing was attempted to be kept to a confined, central area, without the possibility of overlap between the shots. When dealing with certain fabric sample simulations, the firing needed to be carried out in order to keep those conditions as
consistent as possible. This could include factors such as the timing between replicates or the location at which the shots were aimed.

**Fabric and External Temperatures**

**Outdoor Samples.** The first outdoor temperature shooting was carried out under conditions of approximately 45 to 47°F. Samples were kept outdoors at this temperature for about three hours. During the shooting of these samples, drizzling conditions were present. Nylon fabric samples were left unaltered during this phase.

**Indoor Heated Samples.** Exposing the samples to increased heat was carried out by close proximity to a blow dryer set to the highest heat setting. A PRC-Tools Professional 3000 Turbo was set on a stand in front of the mounted fabric sample. With a digital infrared thermometer, the fabric temperature was taken before and after shooting the sample. As was expected, the temperature decreased rapidly once the heat source was removed or turned off. The heated samples were shot at a temperature range from 80 to 106°F, with an average temperature of 100°F.

**Indoor Chilled Samples.** The chilled samples were prepared through overnight storage in a freezer set to 10°F, for approximately 16 hours. Upon removal, samples were immediately transported and set up in the shooting location. The temperature range for these samples was from 49 to 58°F, with an average temperature of 53.6°F.

**Indoor Saturated Samples.** The water-saturated samples were prepared immediately before shooting. The fabric pieces were placed by sample type within a container of water. Samples were removed one by one and mounted while still soaked, although not dripping excess water. The saturated samples were shot at a temperature range of 49 to 55°F, with an average temperature of 53°F.
Outdoor Air Rifle Samples. The outdoor air rifle samples were shot under conditions of 80-81°F. The samples were not exposed to any moisture or other external conditions and were left unaltered during this time.

Firearm and Ammunition

The first outdoor samples were fired with one of two pistols, a 9 mm Glock 19 and a .32 ACP Walther PPK. With the Glock 19, three types of ammunition were fired: 9mm Luger Blazer Brass®, Speer Gold Dot Nickel®, and Herter’s Select Grade Aluminum®. The Walther PPK was used in conjunction with CCI Blazer Brass ammunition.

Outdoor air rifle samples were created through the use of an M417 air rifle. Two air-projectile types were used, Daisy Circular Zinc Plated BBs and Daisy Pointed .177 Cal. Lead Pellets.

Indoor samples were fired with a GSG-1911-22 pistol, as well as a Ruger 10/22 and AK-47 rifle. For the GSG-1911-22, Aguila .22 Super Colibri and Quiet-22 Long Rifle ammunition was used. The Ruger 10/22 was used to fire .22 Thunderbolt ammunition and the AK-47 used Wolf Polyformance® 7.62 x 39mm Steel ammunition. A summary of firearms and their respective ammunition with projectile weights can be found on table 2 below.
Table 2

*Firearm Ammunition*

<table>
<thead>
<tr>
<th>Firearm</th>
<th>Ammunition</th>
<th>Ammunition Weight (grain)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glock 19</td>
<td>9mm Luger: Blazer Brass®, Speer Gold Dot®, Herter’s Select Grade Aluminum®</td>
<td>115, 124, 115</td>
</tr>
<tr>
<td>Walther PPK</td>
<td>CCI Blazer Brass</td>
<td>71</td>
</tr>
<tr>
<td>M417</td>
<td>Daisy Circular Zinc Plated BBs, Daisy Pointed .177 Cal. Lead Pellets</td>
<td>5.1, 7.2</td>
</tr>
<tr>
<td>GSG-1911</td>
<td>Aguila .22 Super Colibri, Quiet-22 Long Rifle</td>
<td>20, 40</td>
</tr>
<tr>
<td>Ruger 10/22</td>
<td>22 Thunderbolt</td>
<td>40</td>
</tr>
<tr>
<td>AK-47</td>
<td>Wolf Polyformance 7.62 x 39mm Steel</td>
<td>123</td>
</tr>
</tbody>
</table>

*Sample Collection and Storage*

Every fabric sample was removed and folded to cover the defects once shooting was complete, then placed in individual plastic bags which were labeled with the shooting conditions. In addition, all shooting conditions were marked on the corner of each fabric sample before removal. Saturated samples were left to dry overnight and then packaged in the same manner as the other samples. Transportation to the laboratories where analysis would take place followed.
Analysis

Stereomicroscopy and Fiber Extraction

Fabric samples were first analyzed on a stereomicroscope in order to conduct a general examination of fiber ends at the margin of the projectile perforations. Fibers from the defects of the samples were carefully cut so as to obtain individual fibers and better analyze fiber characteristics. The extracting of single fibers was done by marking the non-ruptured end under a Nikon SMZ645 stereomicroscope at 5X magnification and proceeding to cut as far away from the defect possible. The fiber was then transferred onto a microscope slide with tweezers. This process was carried out multiple times whenever more fibers needed to be evaluated.

Fiber Mounting

Separated fibers were temporarily mounted by placement on glass microscope slides, covering with a glass coverslip and placing a drop of mineral oil at the corners of the cover slip. Mineral oil was chosen as the mounting medium due to its smaller refractive index difference with nylon which provides improved image quality. Mineral oil has a refractive index of 1.467 (“Liquid Refractive Index”, n.d.). While the refractive index of Nylon 6.6 is 1.53 (“Physical Properties of Plastics”, n.d.). Further examination of the physical, as well as optical, fiber properties was made possible with the various prepared slides.

Polarized Light Microscopy

From there, fiber slides were viewed on a Motic BA310 Pol polarized light microscope, or PLM, under 200 and 400X magnification. The distinction between manually cut and shot fiber ends needed to be made when beginning the analysis process. The rotating stage of the PLM was helpful in finding the correct altered end and then focusing in on it. Once the correct end was located, physical attributes were studied and compared with the cut ends. Photographs of fibers
were taken through the placement of a camera on one the oculars. Confirmation of rapid shear-like characteristics was also done by viewing the defects in their entirety on all nylon sample types with changed environmental conditions and velocity ranges.

To continue with fiber examination, the slides were placed under the PLM with the polarizer and analyzer set perpendicular to one another, or under crossed polars. Along with the affected fibers, intact fibers of the same nylon fabric type were used to have an image of the fiber characteristics before breakage occurred. During this part of the analysis, retardation patterns, orientation and color were recorded, in particular differences in these features between the length of the fiber and its affected, bulbous end. A 530 nm full wave plate was inserted into the PLM to add a one wavelength difference in phase to both polarization directions.

**Scanning Electron Microscopy**

To further evaluate the micromorphology of ruptured fiber ends and obtain images, a Tescan Vega 3XMU scanning electron microscope was employed. Mounted samples went on Zeiss Aluminum specimen mounts with a diameter of 12.7 mm which had double coated, carbon conductive Spectro tabs of a 12 mm diameter to adhere samples. Fibers were cut with both scissors and tweezers in bunches but were separated as much as possible once on the adhesive. Samples were prepared through coating and non-coating methods. A frequent amount of charging artefacts was observed when samples were not coated, this was displayed as white markings on the specimen. Charging can be encountered on an SEM when electrical conductivity is low or an excess of electrons is present on or near the specimen (“Eliminating Charging”, n.d.). Coated samples were prepared with a Cressington 208 carbon coating device. Two detectors were coupled with the instrument, a secondary and backscattered electron detector. Additionally, a beam intensity between 10 and 20.00 kV was used to capture images of samples.
Results

Through each of the microscopical methods employed in this study, physical characteristics previously attributed to rapid shear were found to be present. Defects were seen to be densely populated with mushroom-shaped, melted fiber ends as seen in figures 4, 5, and 6 below. A clear, cap-like bulbous section could be noted at one end of every nylon fiber taken from the perimeter of a fabric defect created by a projectile.

*Figure 4. Single fiber from Nylon 6.6 fabric sample after being shot with 7.62mm steel bullet from an AK-47 at 2300 feet per second. Note bulbous end in circle caused by high velocity tensile fracture. Fabric sample was unaltered (as received from manufacturer). Photo taken in plane polarized light at 200x magnification.*
Figure 5. Two fibers from Nylon 6.6 sample after being shot with Aguila .22 Super Colibri bullet from a GSG-1911-22 at 710 feet per second. Note bulbous ends in circles caused by high velocity tensile fracture. Fabric sample was heated before shooting. Photo taken in plane polarized light at 200x magnification.

Figure 6. Single fiber from Nylon 6.6 fabric sample after being shot with a Daisy circular zinc plated pellet from an M417 at 459 feet per second. Note bulbous end in circle caused by high velocity tensile fracture. Fabric sample was unaltered (as received from manufacturer). Photo taken in plane polarized light at 200x magnification.

These were present in samples shot under all simulated external conditions, with ammunition of varying velocities. The particular characteristics differed from ends which were manually cut in order to extract the fibers. Cut fibers did not display wide, ovular ends but rather clean breaks in non-flared portions, as can be seen in figures 7 and 8 below. Figure 7 displays manually cut fibers which appear flattened due to pressure caused by scissors and tweezers, but no ovular
segments can be seen in the top section of the image. However, in the lower section, mushroom-shaped fiber ends which have been impacted by a projectile are visible. Figure 8 shows some rapid shear affected bulbous fiber ends on the left portion, along with some diagonal, manually cut ends in which the width of the fiber does not appear to increase as the end is approached.

*Figure 7.* Multiple fibers from Nylon 6.6 fabric sample after being shot with Speer Gold Dot® bullet from a Glock 19 at 1225 feet per second. Note difference between bulbous ends in lower portion of image and manually cut end in top portion of image. Fabric sample was saturated with water before shooting. Photo taken in plane polarized light at 200x magnification.
Figure 8. Multiple fibers from Nylon 6.6 fabric sample after being shot with CCI Blazer brass .32 caliber bullet from a Walther PPK at 900 feet per second. Note difference between manually cut fiber end, circled in top portion of image, and bulbous, bullet impacted end, encircled in center portion of image. Fabric sample was unaltered (as received from manufacturer). Photo taken in plane polarized light at 200x magnification.

The specific globular morphological fiber alterations were confirmed with stereomicroscopy, polarized light microscopy and scanning electron microscopy. Images were taken of the affected fibers under a wide range of magnification with all the aforementioned microscope types. Figure 9 represents the visualization of a fiber with a scanning electron microscope.
Figure 9. Single fiber from Nylon 6.6 fabric sample after being shot with Daisy Pointed lead pellet from an M417 at 459 feet per second. Note bulbous end in circle caused by high velocity tensile fracture. Fabric sample was unaltered (as received from manufacturer). Photo taken in scanning electron microscope at ~1,200x magnification.

Under certain conditions, with water-soaked samples specifically, the abundance of globular fiber ends was not noted to be as high as with other samples. However, a large number of those physical features were still visible around the perimeter of the defects. Unaltered, heated, and chilled fabric samples displayed defects with high amounts of mushroom-shaped fiber ends. In some instances, grouped fibers appeared to have fiber ends seemingly melted together in a line through the rapid shear process.

Projectiles were fired at the fabric samples through different mechanisms and at a velocity range from approximately 460 to 2300 feet per second. An air rifle, pistols, and semi-automatic rifles were used in creating exemplar fabric defects. With an air rifle, heat is only
created through frictional forces inside the barrel, so the amount of heat acting on the pellet is negligible. When comparing an air rifle to the propellant ammunition of an AK-47, it is evident that fiber alterations are the result of the high velocity tensile fracture and not a result of heat presence.

Further, the analysis of optical properties with polarized light microscopy revealed substantial differences between fibers and their affected fiber ends. The prepared glass slides with glass coverslips mounted in mineral oil were viewed under crossed polarized light. During analysis, the Michel-Levy chart was referenced to determine the retardation and birefringence ranges observed based on the interference colors displayed. Firstly, a color change was noted when approaching the melted ends, where globular ends showed a partial to complete loss of color. The nylon fibers displayed second order violet and blue colors throughout the length of the fiber but melted ends revealed black, grey, and white coloring which differed drastically. The introduction of black lines at the juncture of fiber and melted end showed the gradual loss of color leading to the ends, as can be seen in figure 10 below. Rapid shear affected fiber ends were categorized in the zero-order black portion of the Michel-Levy interference chart (Bergslien, 2012).
Nylon is an optically anisotropic fiber, meaning it has more than one refractive index, depending on the orientation (Murphy, Spring, Fellers, & Davidson, n.d.). The difference in refractive indices is manifested as birefringence. Evaluating unaffected nylon fibers revealed the anisotropic nature, evident by the birefringent properties exhibited. When viewing the fibers under crossed polarized light, differences in retardation patterns were noticeable from looking at the length of the fiber or unaffected fibers and comparing those to the globular ends. A decrease in retardation was noted on the rapid shear fiber ends when compared with intact fibers by the color change to the zero-order black, indicative of a reduction in birefringence (Bergslien, 2012). Through the evaluation of impacted and non-impacted fibers, it was noted that a non-affected fiber maintained its birefringence and retardation pattern throughout. In contrast, the partially

*Figure 10.* Single fiber from Nylon 6.6 fabric sample after being shot with Quiet-22 long rifle bullet from a GSG-1911-22. Note color change between fiber and widened end. Fabric sample was saturated with water before shooting. Photo taken under crossed polarized light at 400x magnification.
melted fibers had a clear distinction between the fiber and the bulbous, affected end. This distinction is shown in figure 11 below. Visualization of the fibers under crossed polarized light in conjunction with a full wave plate, displayed colors which deviate by one wavelength (Spring, Parry-Hill, & Davidson, n.d.).

![Figure 11](image)

Figure 11. Single fiber from Nylon 6.6 fabric sample after being shot with Aguila .22 Super Colibri bullet from a GSG-1911-22 at 710 feet per second. Note color change between fiber and widened end. Fabric sample was saturated with water before shooting. Photo taken under crossed polarized light with a 530 nm full wave plate inserted at 400x magnification.

In comparison, manually severed nylon fibers exhibited the same interference colors throughout, with no loss of color evident. Figure 12 shows a manually cut fiber with unchanging colors.
Figure 12. Two fibers from Nylon 6.6 fabric sample after being manually cut in the laboratory. Note color consistency through entire fiber. Photo taken under crossed polarized light with a 530 nm full wave plate inserted at 400x magnification.

Throughout this study, the question as to whether rapid shear conditions are universal or can be affected by the environment was evaluated. The work done here was expected to simulate unpredictable weather patterns which are encountered in real life cases. Based on the findings, the external factors implemented did not prevent the rapid shear process from irreversibly altering nylon fiber ends. The shooting was conducted under external temperatures ranging from 46° to 106° F. Additionally, fabric samples were exposed to saturated, heated, and chilled conditions prior to, as well as, during shooting. When studying defect fiber ends, physical and optical characteristics greatly varied from unaltered or mechanically damaged fibers. These features or alteration in features occur as a result of the rapid shear process causing changes to the nylon fibers from the projectile interaction.
Discussion

This research served as a preliminary look at the connection between rapid shear in nylon fibers and extrinsic factors under which fabric defects are generated. Several environmental and external conditions were replicated through this experiment along with a variety of firearms and ammunition. The analysis methods explored with this work can be of a non-destructive nature with regards to fibers. While the defects in a garment (such as might be submitted as evidence in a suspected shooting case) can be viewed as a whole microscopically, the extraction of single fibers was needed in order to take a more in-depth look at the alterations and confirm physical, as well as, optical features.

The importance of this process comes from the type and amount of information which can be gauged from a minimal sample size. An individual or piece of garment may be connected to a location or situation in which shots have been fired through the microscopical analysis of fibers around a single fabric defect. The morphological and optical features provide answers about the origin of fiber fracture and therefore the circumstances to which the garment has been exposed. Ensuring that the rapid shear process is not easily masked by external changes is significant when implementing this method of analysis, as samples submitted may have been present under a wide range of environmental situations. Under microscopical analysis, every defect generated in this study revealed a multitude of fibers containing physical and optical characteristics attributed to the effects of rapid shear.

While external conditions were the focus of this study, they also provided a limiting factor. A general look into ambient, wet, heated and chilled conditions was provided in this study, however, various other scenarios were not simulated at this time. Undergoing shooting with more extreme conditions is necessary to further gauge information and understanding of the
rapid shear process. However, realistic weather conditions were employed with this work as more intense external factors may be encountered less frequently in forensic cases.

In addition to the limit on reproducible conditions, the altered temperatures and fabric conditions of some samples did not endure long enough in the intended state before shooting could occur. This was an obstacle both with the heated and chilled samples. Chilled samples did not appear to retain the colder temperature at which they were incubated. Heated samples quickly lost the higher temperature obtained in the interim before shooting. These situations may be improved if samples are subjected to more intense environmental changes before or during shooting. In an even more complicated scenario, the entire shooting experiment could take place in the specific extreme environmental conditions, but this would require a complex and expensive infrastructure to perform.

Fabric samples which were soaked appeared to retain the intended modification for a more extended period of time. However, future studies looking at the effect of water soaked fabric samples may obtain specific volumes of water in order to detect the exact amount absorbed by the fabric. Changes in volume may indicate if certain amounts of water absorption hinder the rapid shear process in any way.

Through studying and gaining a better understanding of the rapid shear process, garments collected from a scene can be evaluated to determine if they, or the wearer, were in contact with passing bullets. By determining the possible cause of fabric defects, connections or exclusions can be made between the items and certain situations. Research on rapid shear can provide guidelines to the potential methods and possible implementation of this type of analysis requiring minimal sample size and sample destruction.
References


# Appendix

## Glossary

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition (relating to fibers)</th>
</tr>
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<tbody>
<tr>
<td>Anisotropic</td>
<td>A material with more than one refractive index.</td>
</tr>
<tr>
<td>Birefringence</td>
<td>The difference in the refractive indices of an anisotropic substance.</td>
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<tr>
<td>Full wave plate</td>
<td>A type of compensator which works by shifting the interference by one wavelength, or approximately 530 nm.</td>
</tr>
<tr>
<td>Isotropic</td>
<td>A material with only one refractive index.</td>
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<tr>
<td>Michel-Levy Chart</td>
<td>A diagram displaying the interference color spectrum visible under polarized light. A reference for the relationship between a sample and its birefringence, thickness and retardation.</td>
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<tr>
<td>Refractive Index</td>
<td>The ratio of the velocity of light in a vacuum and through a different medium.</td>
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<tr>
<td>Retardation</td>
<td>A measure of the difference in velocities at which two light rays travel through the same medium.</td>
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