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ROBUST ANTI-FOG COATINGS FOR EYEWEAR

by
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Approved for public release; distribution is unlimited.

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The work described herein was performed by the Combat Capabilities Development Center (CCDC) Soldier Center using Core S&T funds during the period October 2017 – August 2020 in support of the Product Manager – Soldier Protective Equipment (PM-SPE) goal of improving durability of antifogging capabilities of protective eyewear. This effort focused on the fabrication and application of textured anti-fog coatings to polycarbonate and nylon substrates which can withstand abrasion and maintain anti-fogging capabilities. The end result was a coating which was substrate-independent in application method and fog performance for 10 seconds when exposed to a humid environment. The coatings did not affect ballistic fragmentation protection of the underlying substrates.

15. SUBJECT TERMS

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FOG
HAZE
LIGHT
LENSES
NYLON
IMPACT
ANTIFOG
EYEWEAR
GOGGLES
COATINGS
GRAFTING
BALLISTICS
THIN FILMS
TROGAMID
PROTECTION
DURABILITY
CONSISTENCY
LOW VELOCITY
TEST METHODS
EYE PROTECTION
PASSIVE ANTIFOG
FRAGMENTATION
POLYCARBONATES
HOT ENVIRONMENT
LIGHT TRANSMISSION
TEST AND EVALUATION
PERFORMANCE(ENGINEERING)
OPTICAL PROPERTIES
SCRATCH RESISTANCE
HUMID ENVIRONMENT
PROTECTIVE EYEWEAR

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Preface

The work reported herein was performed by the U.S. Army Combat Capabilities Development Command Soldier Center (CCDC SC) in support of the Product Manager – Soldier Protective Equipment (PM-SPE) goal of improving durability of antifogging capabilities of protective eyewear. Work was performed during the period October 2018 – 2020 using Core Science and Technology (S&T) funds under the project Robust Anti-Fog Coating for Eyewear (18-212). Current eyewear on the Authorized Protective Eyewear List (APEL) require reapplication of a topical anti-fog solution to help sustain anti-fog properties in the field. Lens fogging in a hectic environment can lead to visual impairment or injury if the eyewear is removed as a result. The focus of this work was to develop a permanent, abrasion-resistant anti-fog coating that does not require a supplemental anti-fog solution for reapplication. The result of this work is an antifog coating which prevents hazing for 10 s and is substrate-independent in application and performance. Coatings did not affect ballistic fragmentation protection.

Acknowledgements

The author would like to thank Michelle Markey and David Ziegler for their technical support on this project.

ROBUST ANTI-FOG COATINGS FOR EYEWEAR

1 Introduction

Eyewear fogs quickly when the temperature difference between the environment and eyewear caused by environmental conditions or lack of airflow causes water vapor to condense on the lens surface. The water droplets create a light scattering haze, which affects visibility.

Current APEL goggles and spectacles require reapplication of a topical anti-fog solution, which can be problematic in the field. In a hectic environment, soldiers have reported that they remove their eyewear once fog has reduced their visibility with the reasoning that they would rather risk an eye injury than risk death as a result of visual impairment [1]. Without fogging, soldiers would not need to doff protective eyewear and would be able to maintain their response time and accuracy during visual exercises in any environment [2].

The work described herein was performed by the Combat Capabilities Development Center (CCDC) Soldier Center using Core S&T funds during the period from October 2018 – August 2020 in support of the Product Manager – Soldier Protective Equipment (PM-SPE) goal of improving the durability of antifogging capabilities of protective eyewear.

The currently used anti-fog coatings are superhydrophilic. Instead of beading up on the surface, the water is instead spread into a thin, even film, which minimizes the disruption to light transmittance. The work described herein focuses on creating a superhydrophilic surface that can be permanently grafted onto a substrate, thus preventing the need for reapplication. It has been shown that using a breath figure array (BFA) method of creating a porous thin film can lead to coatings with multifunctional and hierarchal morphologies [3]. This is done by casting a polymer solution onto a substrate and allowing it to dry in a hot, humid environment as demonstrated in Figure 1 [3]. The pores of the BFA films can be functionalized to give the film desired properties and the film can be crosslinked after formation to increase durability of the coating. The textured structure of the surface also creates a hem-wicking effect which decreases the contact angle of water droplets and aids in spreading the fog into a thin film.

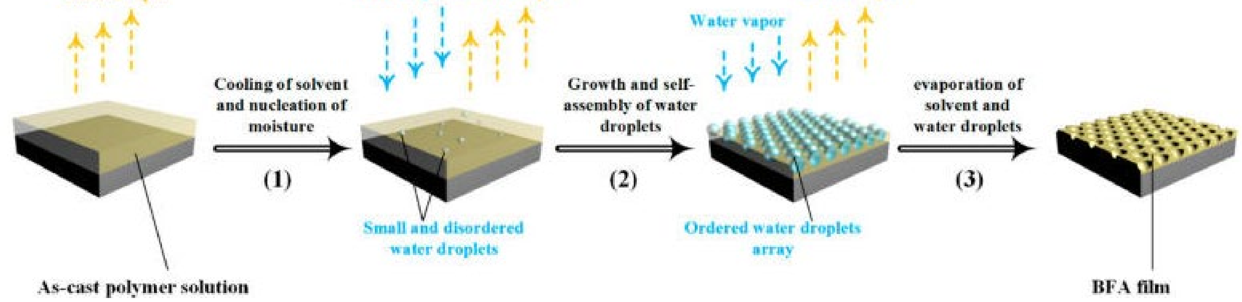

Figure 1 - Formation process for BFAs [3]

The impact of this work is an advancement in the knowledge of tailored coatings that address the Warfighter needs to improve eye protection.

2 Materials

Coatings:
Polystyrene (PS), 250k molecular weight (MW), Acros Organics
Silicon dioxide (SiO_2) nanoparticles, 5-15 nanometer (nm), Aldrich Chemical Company, Inc.
SiO_2 nanoparticles, Nissan Chemical Company
Pluronic® F87 Prill, BASF Corporation
Pluronic® P123, BASF Corporation
Pluronic® P103, BASF Corporation
Polyurethane, Covestro Texin
Poly(styrene)-block-poly(acrylic acid), azide terminated (PS-*b*-PAA), Sigma
Silver (Ag) nanoparticles, 50-80 nm, US Research Nanomaterials
PS, amine-terminated, M_n 5000, Aldrich Chemical Company, Inc.
Acetone, VWR
Ethanol, Aldrich Chemical Company, Inc.
Tetrahydrofuran (THF), Sigma Aldrich
Toluene, BDH
Chloroform, Sigma Aldrich
Polytetrafluoroethylene (PTFE), 1 um, Aldrich Chemical Company, Inc.
Poly(allylamine hydrochloride) (PAH), Alfa Aesar
Polyacrylic acid (PAA), 50k MW, 25% in water, Polysciences, Inc,
Poly-diallyldimethylammonium chloride (PDDA), Sigma Aldrich
Deionized (DI) water, RiOs™ 16, Millipore
Polyethylenimine (PEI) branched, MW 25k, Aldrich Chemical Company, Inc.
Esacure DP250, IGM Resins
Ucecoat® 6569 polyurethane, Allnex
2N Hydrochloric acid (HCl), Sigma
5N Sodium Hydroxide (NaOH), EMD
Polystyrene-*b*-polybutadiene (PS-*b*-PB), Sigma Aldrich

Substrates:
BPA Polycarbonate, Revision Military, LTD
Trogamid®, Evonik-Degussa Inc.
Glass slides
Wiley-X spectacles, Wiley-X, Inc.
Revision Desert Locust goggles, Revision Military, LTD

Equipment:
4th Generation Fog Test Apparatus
Pencil abrader – Summers Optical 2.5 lb Test Instrument
Harrick plasma cleaner model PDC-32G
AFM, VEeco diNanoscope V, silicon tip on a nitride lever
Keyence optical light microscope
Espec environmental chamber, model SH-242
Low velocity gas gun with 5.85 grain fragment simulating projectiles (FSP) and 17 grain FSP, T37 shape
Ultraviolet (UV) lamp, 254 nm wavelength, Analytik-Jena

3 Methods

3.1 Methods of coating

Multiple methods of coating the substrates were explored in order to obtain a consistent coating between samples. It is also important that the method is suitable for commercial application. For BFAs, solutions of polystyrene (PS) in toluene were applied to substrates using a spray bottle, a spreader bar, a paint brush, and by dip coating. It was found that dip coating was the most consistent method that left no streaks or concentrated areas. Polycarbonate (PC) and nylon are hydrophobic and thus are difficult to wet without solvent beading up on the surface. The use of air plasma creates polar –COOH and –OH groups on the substrate surface and increases the surface energy and wettability [9]. Plasma treating for 5 to 8 min before coating allowed for uniform application of polymer solutions.

3.2 Solvent type

Besides having anti-fogging properties, the coatings must also be able to be applied to a substrate in a commercial setting. While dip or spray coating using a solvent are convenient methods of applying a coating, some solvents may damage plastic substrates and affect the ballistic fragmentation protection properties of the eyewear. For this reason, multiple solvents were used in order to determine compatibility with the PC and Trogamid® (nylon) substrates.

Some experiments were carried out on Wiley-X commercial spectacle lenses, which have an anti-scratch coating on the outer surface. Chloroform peeled the coating off and would therefore not be a good candidate for a solvent if used in conjunction with some manufacturer coatings.

Ethanol left white films on both the PC and Trogamid® substrates and was also eliminated as a potential polymer solvent. It was also determined from experiments that acetone is not suitable for PC, but is compatible with Trogamid®.

3.3 Concentration effect

The effect of polymer concentration in solvent played a role in coating quality and effectiveness. The coating must be thick enough to provide anti-fogging capabilities and form a porous or capillary-like structure, but must also be thin enough to prevent streaking or a haze from forming on the substrate.

On polycarbonate, solutions of amine-terminated PS and PS-b-PAA at 0.1 wt% in chloroform left a thick, white film. The same solutions on Trogamid® left transparent but streaky coatings. Diluting the solutions to 0.01 wt% mitigated these problems. This is easily adjusted for layer-by-layer (LbL) coatings, which can have any desired number of bilayers but must be more carefully controlled for BFA coatings.

3.4 Breath figure arrays

Solutions of Pluronic® in various solvents and concentrations were a simple and inexpensive method of exploring application methods, solvent compatibility, and concentration effect on optical properties while also looking at the effectiveness of Pluronic® as an anti-fog solution. Pluronic® is a tri-block copolymer often used as a surfactant for many applications, including anti-fogging [10, 11]. The following solutions were prepared using Pluronic® P123 and F87 Prill:

- 0.5 wt% in acetone
- 0.1 wt% in THF
- 1 wt% in toluene

PC, Trogamid®, and glass substrates were plasma treated for 5 min. Solutions were sprayed, dip-coated, or 10 µL of solution was manually spread onto the substrates with a brush. They were immediately placed in a conditioning chamber at 80% RH and 30-35 °C to dry. These conditions were selected based on literature recommendations. Drying time was a minimum of 30 min.

PS is also known to form BFA films and was another polymer system prepared in multiple solvents and concentrations [12, 13]. It has also been shown that the addition of Ag nanoparticles affects assembly of the films [8] and that the nanoparticles arrange themselves on the inside of the pores [14]. The introduction of Si and SiO_2 nanoparticles into BFAs has been shown to stabilize the structure of BFAs [3], create a hydrophilic surface [15], and may aid in preventing scratching. Studies have also shown that PS with functionalized end groups improves the regularity of the porosity in the BFA film as compared to non-functionalized PS [13]. The following PS coatings were prepared:

- 1 wt% 25k MW PS and 0.01 wt% SiO_2 nanoparticles in toluene; PC and glass substrates were plasma treated for 5 min, 10 µL of solution was manually spread on the surface using a brush and the substrates were placed in a conditioning chamber at 80% RH and 30 °C to dry.
- 1 wt% 250k MW PS and 0.01 wt% Si nanoparticles in toluene; PC and glass substrates were plasma treated for 5 min, 10 µL of solution was manually spread on the surface using a brush and the substrates were placed in a conditioning chamber at 80% RH and 30 °C to dry.
- 0.1 wt% amine-terminated PS in chloroform; PC and Trogamid® substrates were plasma treated for 6 min, dipped in solution, and placed in a conditioning chamber at 80% RH and 35 °C to dry
- 0.01 wt% amine-terminated PS in chloroform; PC and Trogamid® substrates were plasma treated for 6 min, dipped in solution, and placed in a conditioning chamber at 80% RH and 35 °C to dry
- 1 wt% amine-terminated PS in toluene; PC and Trogamid® substrates were plasma treated for 6 min, dipped in solution, and placed in a conditioning chamber at 80% RH and 35 °C to dry
- 0.1 wt% amine-terminated PS and 0.01 wt% Ag nanoparticles in chloroform; PC and Trogamid® substrates were plasma treated for 6 min, dipped in solution, and placed in a conditioning chamber at 80% RH and 35 °C to dry
- 0.01 wt% amine-terminated PS and 0.01 wt% Ag nanoparticles in chloroform; PC and Trogamid® substrates were plasma treated for 6 min, dipped in solution, and placed in a conditioning chamber at 80% RH and 35 °C to dry

Another polymer of interest is PS-*b*-PAA. It is a naturally hydrophilic polymer which can form BFAs and is stable at high temperatures and resistant to solvents [16]. The following solutions using PS-*b*-PAA were prepared:

- 0.1 wt% in toluene
- 0.01 wt% in toluene
- 0.01 wt% in THF

- 0.1 wt% in chloroform
- 0.01 wt% in chloroform
- 0.01 wt% plus 0.01 wt% Ucecoat 6558 and 0.01 wt% Esacure DP250 in THF, substrates were UV cured with a 254 nm wavelength lamp for 20 s after drying
- 0.01 wt% in THF, after drying the substrates were dipped in an aqueous solution of 0.01 wt% Ucecoat 6558 and 0.01 wt% Esacure DP250 and were UV cured for 20 s after drying

The PC and Trogamid® substrates were plasma treated for 6 min and then dipped in each solution. They were immediately placed in a conditioning chamber at 80% RH and 35 °C to dry.

The same BFA process noted above was also performed for a 1 wt% solution of PU with 0.01 wt% Ag nanoparticles in toluene and a solution of 1 wt% PAA and 0.01 wt% SiO_2 nanoparticles in toluene.

3.5 Layer-by-layer coatings

The layer-by-layer (LbL) method of creating thin films has been shown to create porous polymer networks that can be functionalized to obtain the desired hydrophilic properties [4, 5]. The addition of SiO_2 nanoparticles create a hydrophilic antifogging surface with a low refraction index [15]. In order to create LbL films, the following solutions were prepared:

- wt% PAH in water
- 0.01 wt% PAA in water
- 0.01 wt% PDDA in water
- 45 mg/mL PTFE in ethanol
- 3 mg/mL SiO_2 nanoparticles in acetone
- 0.01 wt% PAH and 0.3 wt% SiO_2 nanoparticles in acetone

Solutions containing nanoparticles were sonicated for 45 min and then adjusted to pH 4 using 2N hydrochloric acid. All other solutions were mixed using a magnetic stir bar.

Glass, polycarbonate, and Trogamid® substrates were coated with two variants of LbL films. Each substrate was plasma treated for 8 min prior to dip coating. Each coat of polymer substrate was followed with a rinse in DI water and then allowed to air dry for approximately 10 min before applying the next coating in an effort to avoid buildup of excess polymer, which can leave a haze on the substrate.

The first coating consisted of a layer of PAH followed by PAA, PAH/SiO_2, and PAA. This sequence was repeated for a total of eight layers. The second coating consisted of PDDA, SiO_2, PDDA, and PTFE. These four layers were repeated for a total of eight layers. The coatings on PC substrates were either opaque or cloudy, but appeared to hold up well against abrasion. The coatings on Trogamid® were clear. PDDA/SiO_2/PDDA/PTFE coatings on Trogamid® produced fogging when subject to a breath test. The breath test served as a quick means of assessing whether the lens had some anti-fog properties by simply breathing out closely to the lens surface and observing whether or not the lens fogged and, if so, how quickly the fog dissipated. Lenses with no anti-fog properties will readily fog when subjected to the breath test, and dissipate slowly once the test is complete. The PAH/PAA/PAHSiO_2/PAA coatings on Trogamid® either fogged and cleared quickly or showed minimal fogging when subject to a breath test and were therefore selected for further testing with the 4th Generation Fog Test Apparatus.

The polymer PEI is known to adhere well to most substrates when used as a base layer in LbL films [6]. It was hypothesized that this could improve adhesion of coatings to the substrate. It has also been shown that Esacure DP250, a water-soluble photoinitiator, mixed with Ucecoat® 6558, a UV-curable polyurethane, could act as a durable cross-linked matrix within a LbL matrix [7]. The following solutions were prepared:

- wt% PEI in water
- 0.01 wt% PAA in ethanol
- 3 mg/mL SiO_2 nanoparticles in ethanol
- 0.01 wt% Ucecoat 6558 and 0.01 wt% Esacure DP250 in ethanol

Glass, polycarbonate, and Trogamid® substrates were plasma treated for 8 min to improve wettability, then dipped in the PEI solution. They were rinsed with DI water and allowed to dry before dipping in the PAH/SiO_2 solution followed by the Ucecoat® 6558/Esacure DP250 solution. The coatings were then UV cured with a 254 nm lamp for 20 s. These coatings left a white film on PC and Trogamid® substrates. These coatings were clear and showed anti-fog performance when applied to a glass substrates.

SiO_2 nanoparticles layered with PAH has been shown to produce hydrophilic and capillary properties when multiple bilayers are applied to a substrate [5]. For this purpose, the following solutions were prepared:

- 0.03 wt% SiO_2 in water adjusted to pH 9 using NaOH
- 0.05 wt% PAH in water adjusted to pH 2 using HCl
- 0.05 wt% PAA in water adjusted to pH 2 using HCl

The polycarbonate and Trogamid® substrates were plasma treated for 6 min before coating to improve wettability. Each substrate was then dipped in the PAH followed by PAA. Next, a total of eight bilayers of PAH and SiO_2 nanoparticles were applied. The substrate was submerged in each solution for 5 min then rinsed in DI water by gently swirling before dipping in the next solution. These coatings fogged but cleared quickly when applied to polycarbonate.

3.6 Tests

3.6.1.1 Imaging

Atomic force microscopy (AFM) was used to view the coatings and verify that a porous film was formed. Images were taken at a minimum of three points on a substrate. An optical microscope was also used to view coatings and measure pore sizes where appropriate.

3.6.1.2 Abrasion

Abrasion was performed using a Summers Optical 2.5 lb Test Instrument with standardized eraser as specified in Military Combat Eye Protection (MCEP) System Performance Specification MIL-PRF-32432 Section 4.4.3.4.3.1. The eraser was held roughly normal to the substrate surface and passed over the surface for 20 (back and forth) cycles with a force of 2 to 2.5 lb. This process was repeated multiple times on a given substrate in order to obtain an abraded area large enough to test with the Fog Test Apparatus.

3.6.1.3 Fog testing

Anti-fog performance was tested using the 4th Generation Fog Tester developed by CCDC Soldier Center. Currently fielded APEL eyewear was used as a baseline for performance. Samples were mounted on a headform inside a temperature and humidity controlled unit. Substrates were placed inside the unit to acclimate to the conditions for a minimum of 30 min before testing. A camera inside the eye of the headform records images of an NBS-1952 Resolution Test Chart used to determine the resolution power of the lenses. The camera records images of the chart over a course of 30 s as hot, humid air is directed at the substrate to induce fogging. The contrast ratio for resolution line 40 is reported as a function of time. Samples were tested in triplicate.

3.6.1.4 Ballistic fragmentation tests

A limited ballistic test was done on down-selected coatings to confirm that coatings did not affect the ballistic fragmentation characteristics. Testing was performed using a helium gas gun at velocities specified in the MCEP System Performance Specification MIL-PRF-32432 Section 4.4.3.3 using a 5.85 grain 0.15 caliber T37-shaped FSP and 17 grain 0.22 caliber T37-shaped FSP. The 5.85 grain target velocity was 640-660 ft/s and the 17 grain target velocity was 550-560 ft/s. If the first shot was a partial penetration, a second shot was taken.

4 Results and Discussion

4.1 Imaging

Since the formation of pores is an important method of creating a low contact angle through a hemi-wicking effect, an optical microscope and AFM were used to look at the surface structure of the films. Figure 2 shows microscope images of PS BFAs before and after abrasion. It can be seen that pores are formed and that the pore structures can withstand abrasion. However, scratches can be observed on the remainder of the film, which will increase haze.

Figure 3 shows a microscope image of PU BFAs with and without Ag nanoparticles. This suggests that the addition of the nanoparticles can affect the formation of the BFA structure and can therefore in future work be more carefully explored as additives for anti-fog films.

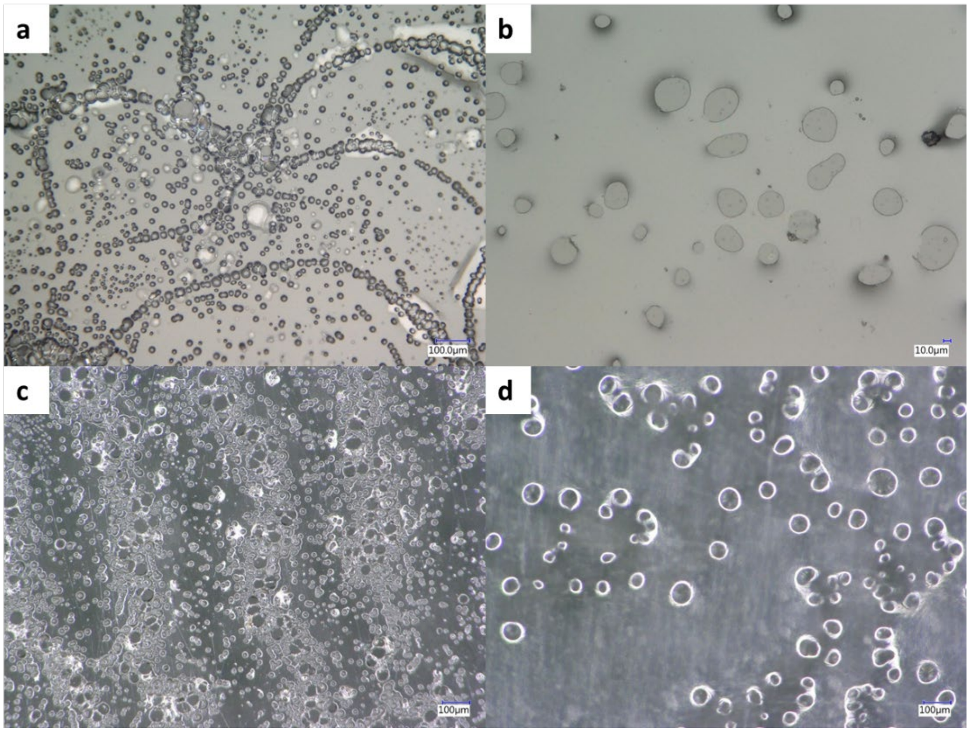

Figure 2 - Optical microscope images of (a) 250k MW PS BFA, (b) 25k MW PS BFA, (c) 250k MW PS BFA after abrasion, and (d) 25k MW PS BFA after abrasion

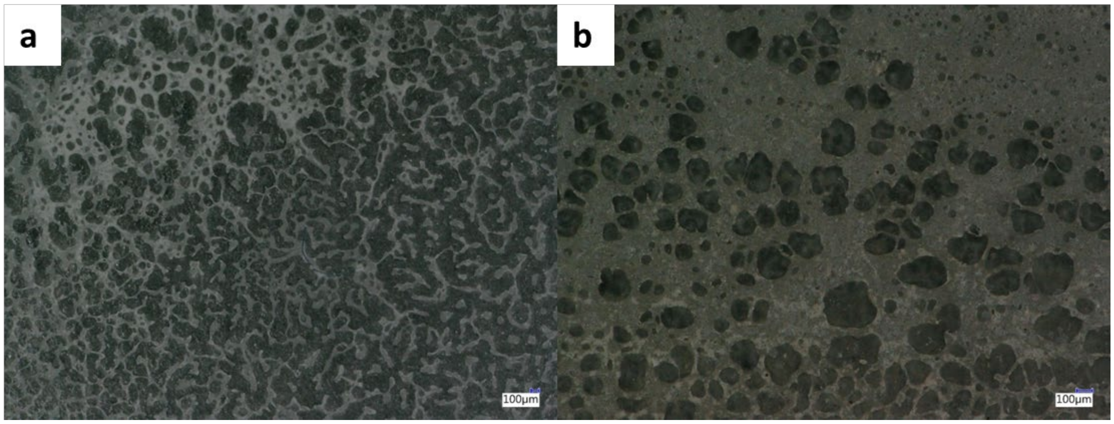

Figure 3 - Optical microcope images of (a) PU BFA in THF and (b) PU and Ag nanoparticles BFA in THF

Figure 4 shows the effect of the application method on the formation of BFAs. Spraying left concentrated areas of solution and would therefore not be an appropriate method for applying coatings. Dipping appears to create the most uniform structure and can be feasibly used in a commercial setting.

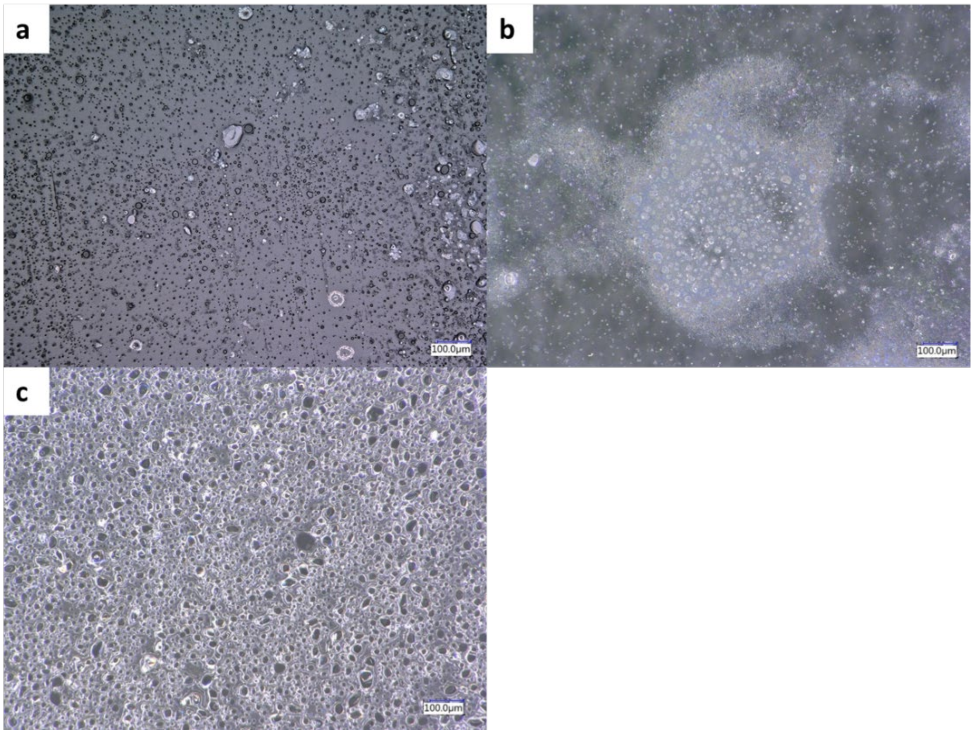

Figure 4 - Optical microscope images of 25k MW PS BFA that were applied via (a) manual spreading, (b) spraying, and (c) dipping.

AFM was also used to examine the uniformity of pores as shown in Figure 5. Figure 5a shows clear pore formation of a PS-b-PB BFA. Figures 5b and 5c show that the Pluronic® and PAH/SiO_2 form textured surfaces but are not necessarily porous.

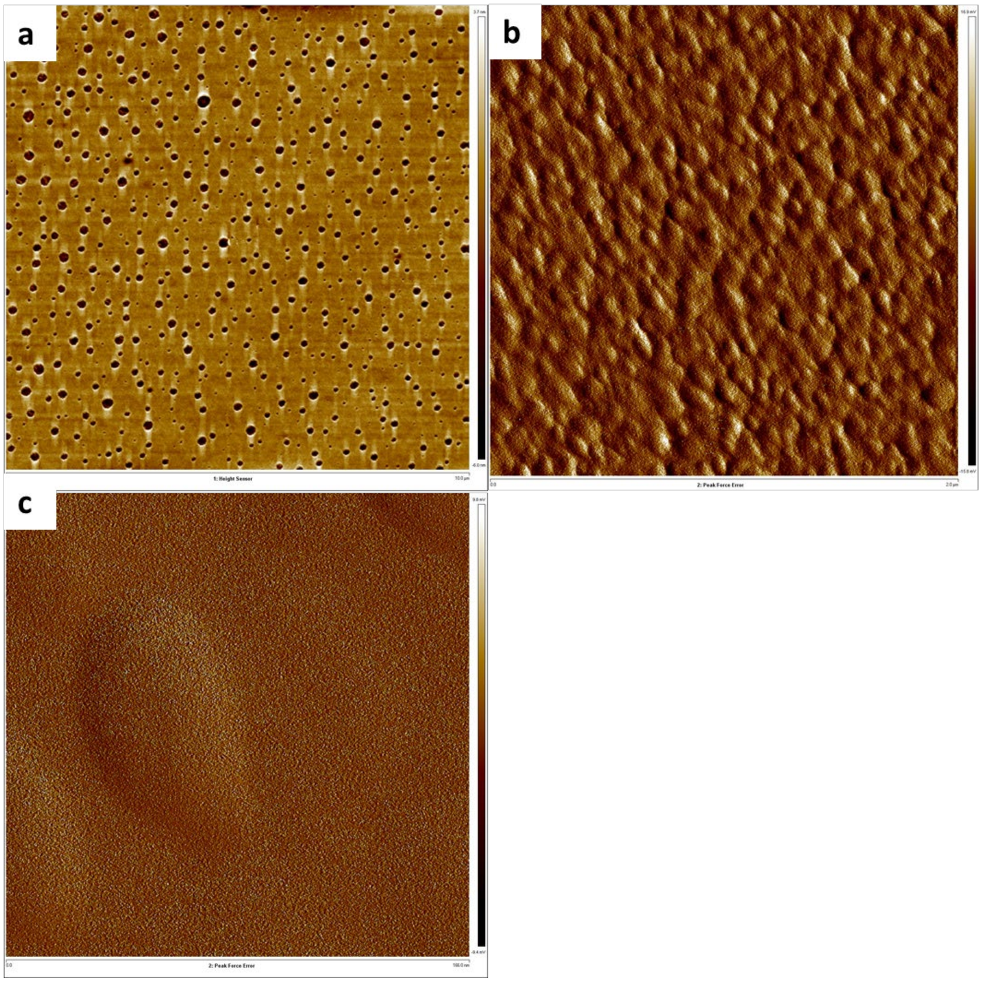

Figure 5 - AFM images of (a) PS-b-PB BFA, (b) Pluronic® P123, and (c) PAH and SiO_2 nanoparticles BFA

4.2 Fog testing

The ability of a formulation to provide anti-fog performance was first approximated by breathing onto the substrate and observing whether or not it fogged. Substrates that did not pass a “breath test” were not tested using the 4th generation fog test apparatus.

Figure 6 shows the fog test results for BFA coatings with % haze references. A relatively flat line is desirable as it indicates that fogging does not occur over time. The Pluronic® coatings performed well in this sense but the initial high haze indicates that more work needs to be done on optimizing the coatings so that they are thin enough that they do not affect the initial haze measurements of the underlying substrate.

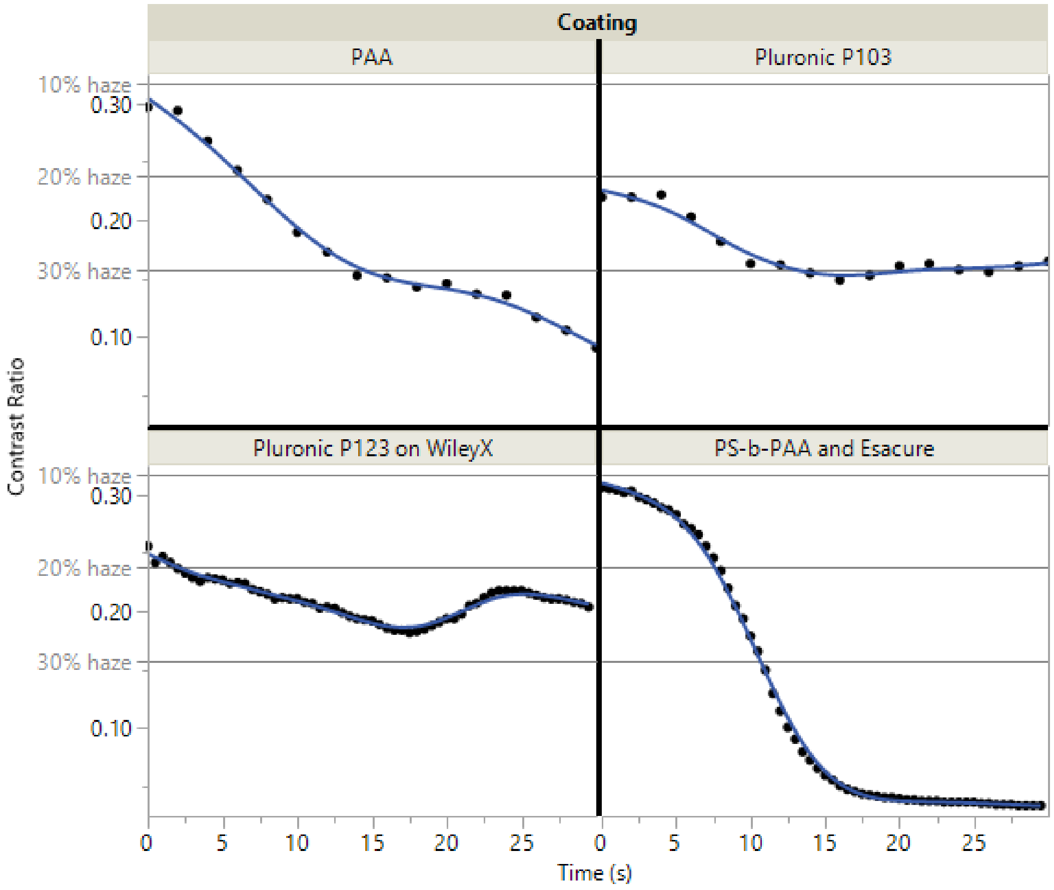

Figure 6 - Anti-fog performance over time for BFA coatings

Figure 7 shows the fog test results for the LbL solutions with % haze as references. The PEI/PAH/SiO_2 performed the best and maintained anti-fogging performance over the course of 30 s. The PAH/PAA/PAHSiO_2/PAA coating also maintained a steady performance but had a high initial haze. This may have been because the film was too thick. It therefore might be possible to optimize the concentrations and bilayer number of the films to start with a clearer coating.

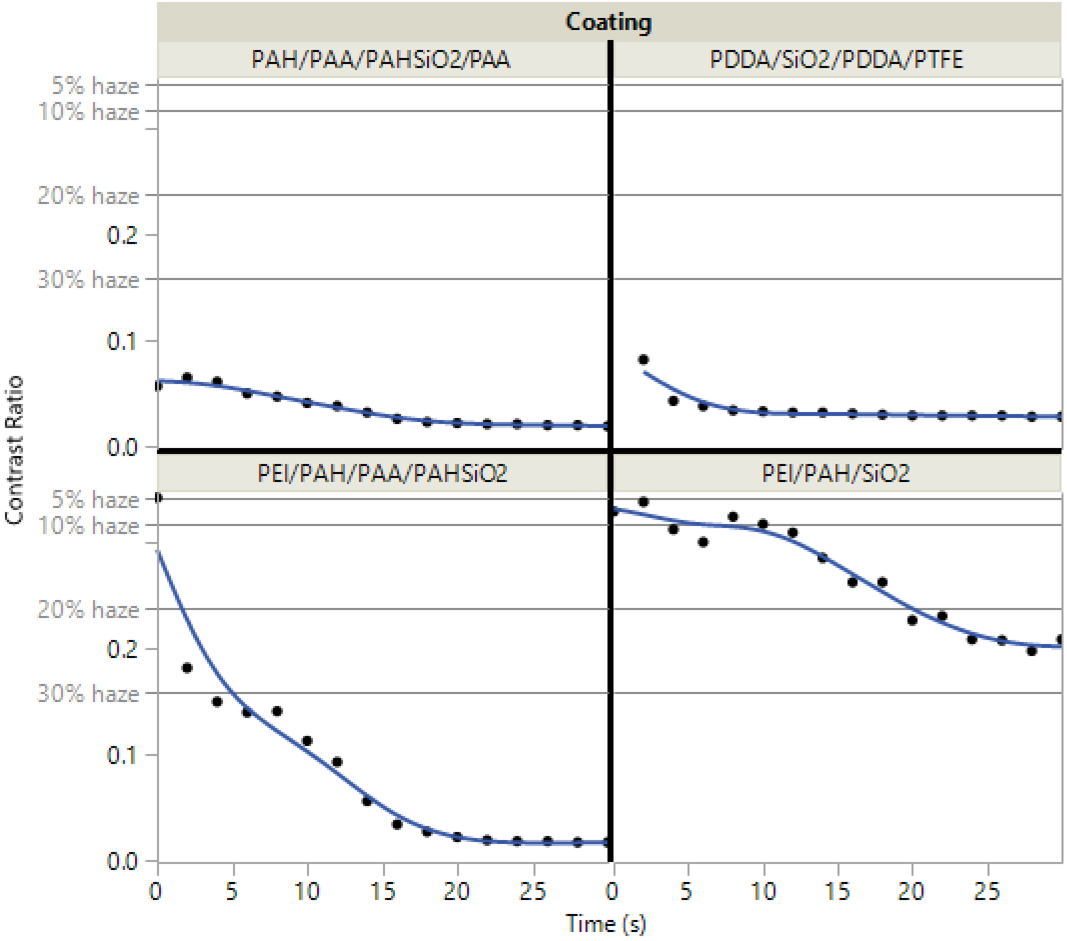

Figure 7 - Anti-fog performance over time for LbL coatings

Figure 8 shows the performance of select coatings before and after abrasion using the standardized eraser. Both coatings tested on the PC substrates significantly decreased in performance when abraded, but the Pluronic coating on Trogamid® remained relatively the same. This could be an indication that coatings are substrate-dependent. It may also indicate that without an anti-scratch coating first applied to the substrate, the anti-fog coatings will do little to protect the underlying material from abrasion.

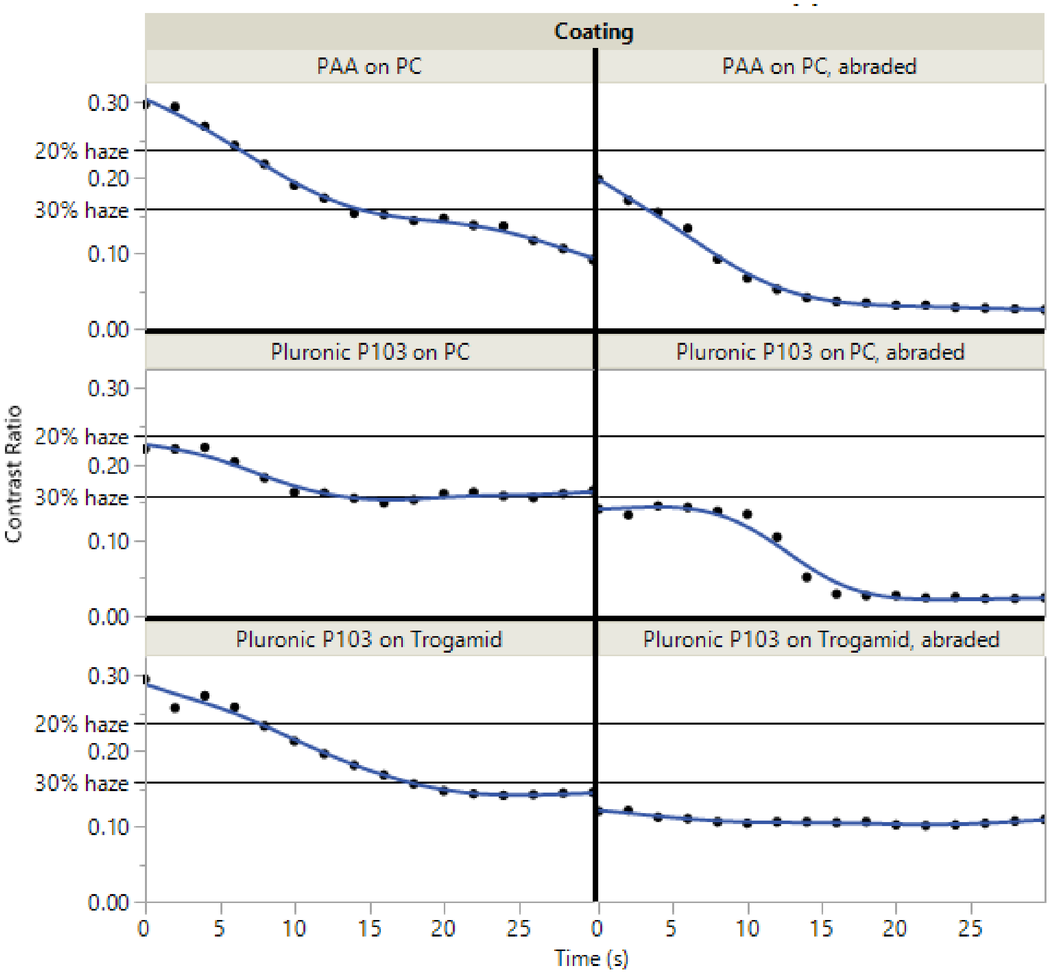

Figure 8 - Anti-fog performance of select coatings before and after abrasion over time

Based on these results, four coatings were downselected for additional fog testing and ballistic fragmentation testing.

4.3 Preparation of downselected coatings

The following solutions were prepared in order to create final samples:

- 0.05% PAA in water, adjusted to pH 2 with HCl
- 0.1% PEI in water
- 0.03% SiO_2 nanoparticles in acetone, adjusted to pH 4 with HCl
- 0.07% PAH in water, adjusted to pH 2 with HCl
- A mixture of the SiO_2 and PAH (50%/50% by volume)
- 0.125% Pluronic® P103 in water

First, antifog coatings were removed from the Trogamid substrates by washing in acetone. All substrates were plasma treated with air in a Harrick plasma cleaner for 5 min before coating. All substrates were dipcoated. A minimum of three substrates per coating were prepared for fog and fragmentation tests. For layered coatings, substrates were dipped in DI water in between each layer to remove any poorly adhered polymer. Samples were allowed to air dry.

Coating 1: Pluronic® P103
One layer of Pluronic P103 was applied to each substrate by dip coating.

Coating 2: PEI/(PAH/SiO_2)2
An initial coating of PEI solution was applied. Next, the substrates were dipped in a layer of PAH followed by SiO_2 twice for a total of five polymer layers.

Coating 3: PAA
One layer of PAA was applied to each substrate by dip coating.

Coating 4: PEI/(PAH/PAA/PAHSiO_2/PAA)2
An initial coating of PEI was applied. Next, substrates were dipped in the following solutions twice through for a total of nine polymer layers: PAH, PAA, PAH/SiO_2, and PAA.

4.3.1 Downselected coatings fog testing

Samples prepared above were tested in triplicate using the 4th generation fog test apparatus. Results are shown in Figures 9 and 10 with a 5% haze reference line. Coatings on PC shown in Figure 9 were consistent in performance, suggesting that the coating process can be repeated for uniform and consistent results. Figure 10 shows the same coatings on Trogamid substrates. Performance was less consistent for the Trogamid® substrates. This may have been due to scuffing on the surface caused by removing the original anti-fog coatings. Any residual coating or scuffs on the surface might affect the adhesion of the applied coatings. The use of a pristine substrate may mitigate this issue.

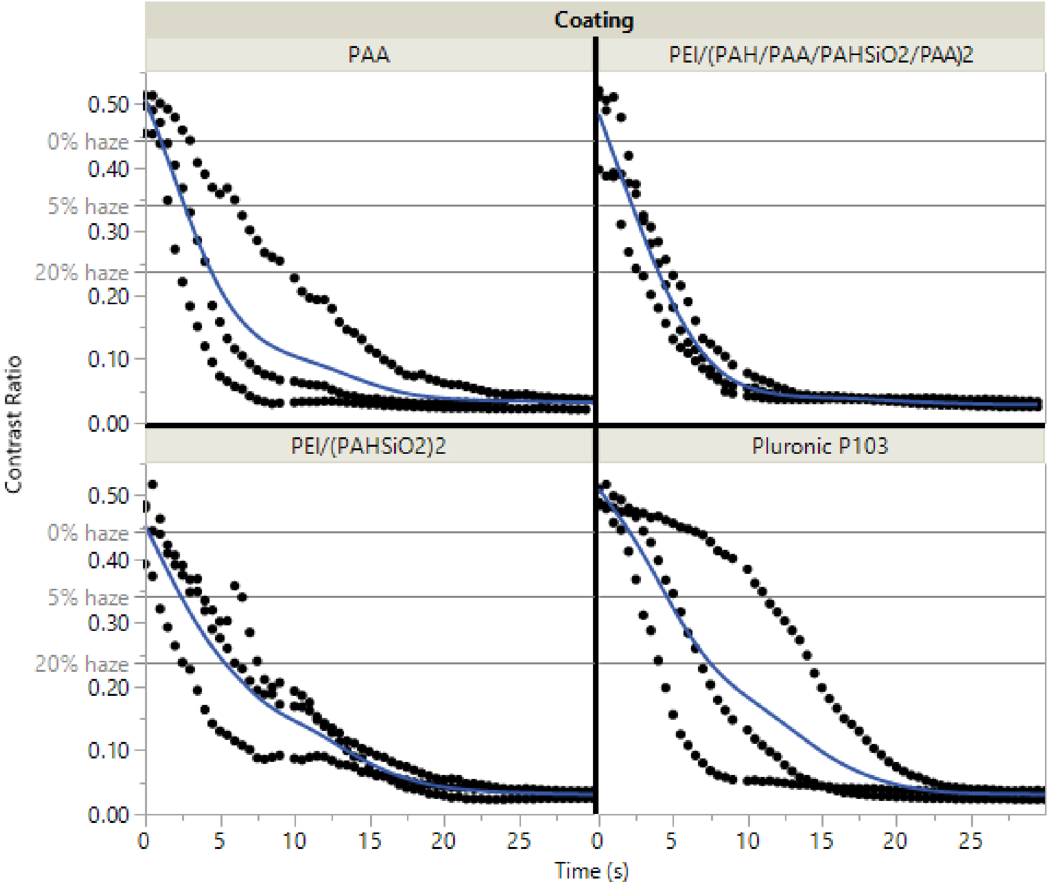

Figure 9 - Contrast ratio vs time for downselected coatings on polycarbonate substrates

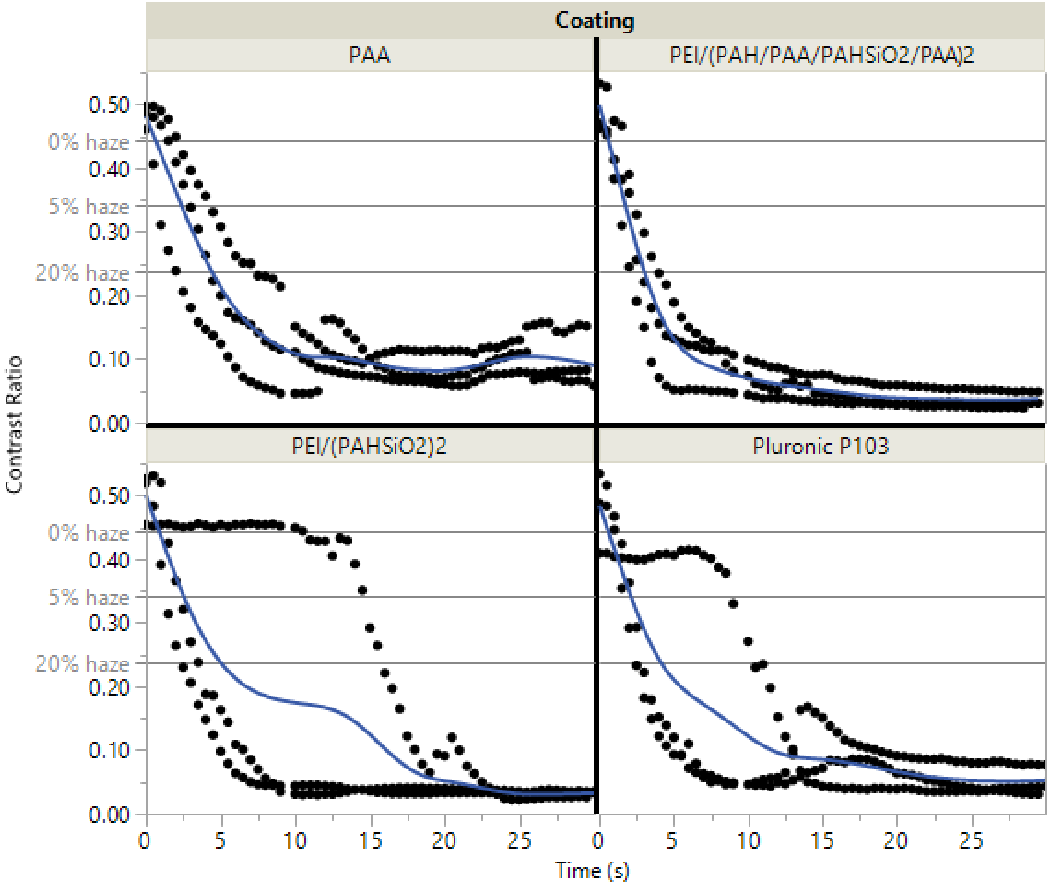

Figure 10 - Contrast ratio vs time for downselected coatings on Trogamid® substrates

Figure 11 shows a comparison of the performance for the coatings on PC and Trogamid® substrates. There is little variation in the coatings' anti-fog properties between the two substrates, which suggests that the coatings are substrate-independent.

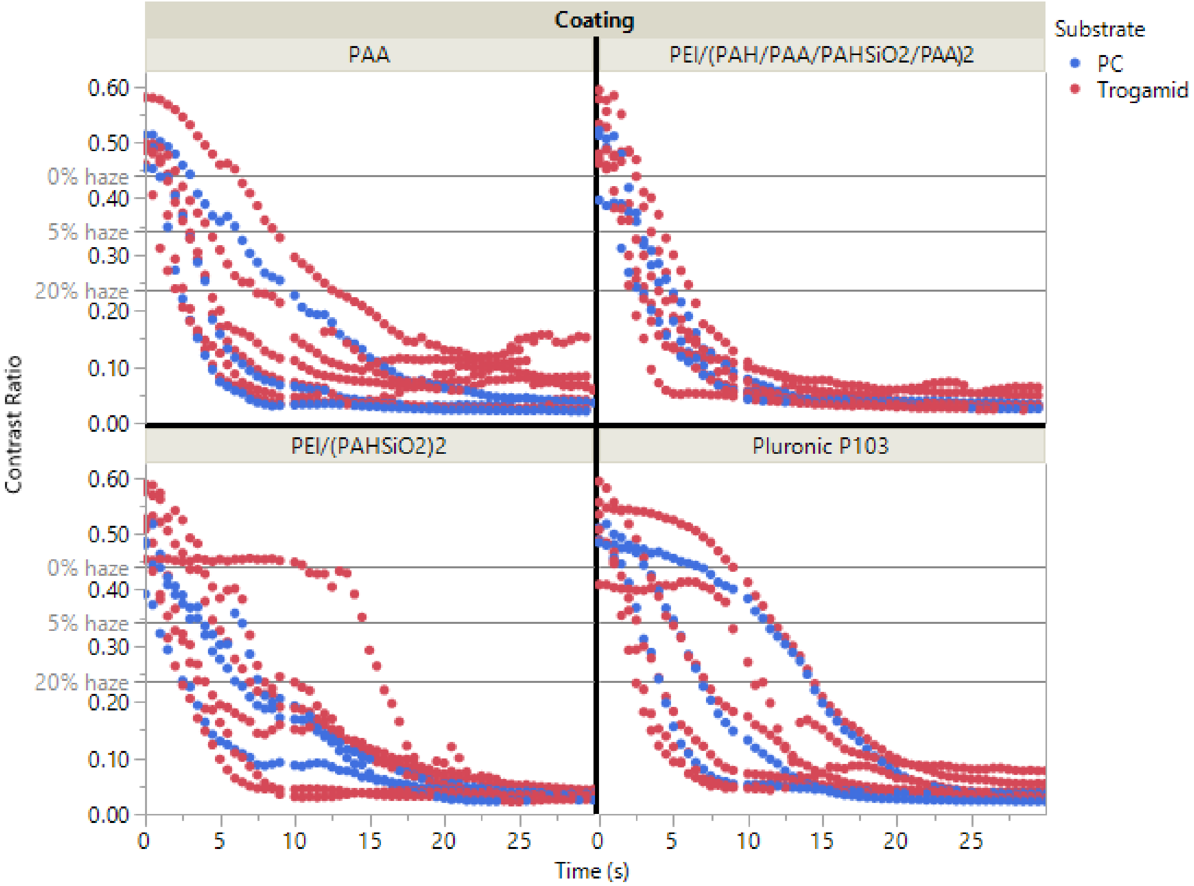

Figure 11 - Downselected coatings on PC (blue) and Trogamid® (red)

4.4 Ballistic fragmentation on downselected coatings

The striking velocities and results of the fragmentation tests are outlined in Tables 1 and 2. A "P" indicates a partial or no penetration and "CP" indicates a complete penetration. For samples where the first impact was a partial penetration, a second shot was taken. The "P" highlighted in Table 1 indicates a sample where the second shot stopped the projectile, but the sample shattered upon impact. The CP highlighted in Table 2 indicates a high striking velocity and can be considered an outlier.

Table 1 - 17 grain FSP ballistic results

17 gr, 0.22cal FSP					
Coating	**Substrate**	**Velocity 1 (fps)**	**P/CP**	**Velocity 2 (fps)**	**P/CP**
None	PC	540	P	559	P
		544	P	549	P
	Trogamid	564	P	554	P
Pluronic 103	PC	575	P	547	P
		572	P	541	P
		561	P	552	P
		572	P	543	P
	Trogamid	552	**CP**		
		523	P	553	P
		530	P	544	**CP**
		582	**CP**		
PEI/(PAH/SiO2)	PC	534	P	542	P
PEI/(PAH/PAA/PAH SiO2/PAA)	PC	536	P	551	P
	Trogamid	555	P	558	**P**

Table 2 - 5.85 grain FSP ballistic results

5.85 gr, 0.15cal FSP					
Coating	**Substrate**	**Velocity 1 (fps)**	**P/CP**	**Velocity 2 (fps)**	**P/CP**
None	PC	421	P	600	P
		484	P	521	P
	Trogamid	641	P	729	P
Pluronic 103	PC	632	P	384	P
		713	P	946	**CP**
		683	P	697	P
	Trogamid	291	P	699	P
		630	P	653	P
		707	P	523	P
PEI/(PAH/SiO2)	PC	708	P	665	P
		487	P	738	P
		708	P	692	P
	Trogamid	646	P	673	P
		667	P	716	P
		698	P	720	P
PAA	PC	748	P	673	P
		700	P	698	P
		684	P	444	P
	Trogamid	708	P	669	P
		591	P	713	P
		690	P	627	P
PEI/(PAH/PAA/PAH SiO2/PAA)	PC	702	P	672	P
		719	P	443	P
		672	P	701	P
	Trogamid	741	P	652	P
		748	P	716	P
		683	P	581	P

Images of the shot samples can be found in the Appendix. The results suggest that the coatings were not detrimental to the ballistic performance of the substrates, as all met the 5.85 gr ballistic fragmentation performance requirements. The Trogamid® substrates did not meet 17 gr ballistic fragmentation protection requirements for the Pluronic® P103 coating. Since the goggle samples were cut into sections for coating, this could cause inconsistencies in sample thickness and curvature between shots which could explain the poorer performance of some samples against the 17 gr FSP.

5 Conclusions

Two coating methods were explored for the purposes of creating a robust anti-fog coating for protective eyewear. Both methods of creating BFAs and multilayered coatings created textured, wicking surfaces which are meant to create a thin film of water to prevent fogging during temperature changes. PAA demonstrated the best anti-fog performance on both PC and Trogamid® coatings. Coatings did not affect the ballistic performance of the underlying substrates.

This document reports research undertaken at the U.S. Army Combat Capabilities Development Command Soldier Center, Natick, MA, and has been assigned No. Natick/TR-21/007 in a series of reports approved for publication

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Appendix

Images of shot samples

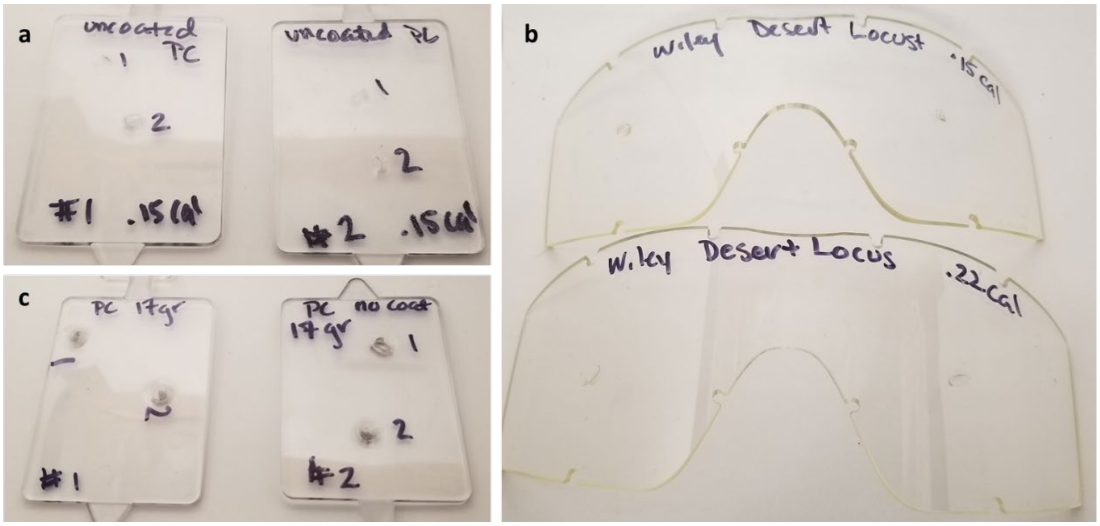

Figure A-1 – (a) Uncoated PC plaques against 5.85 grain FSP, (b) As-received Revision Desert Locust goggles against 5.85 grain (top) and 17 grain (bottom) FSPs, (c) uncoated PC plaques against 17 grain FSP.

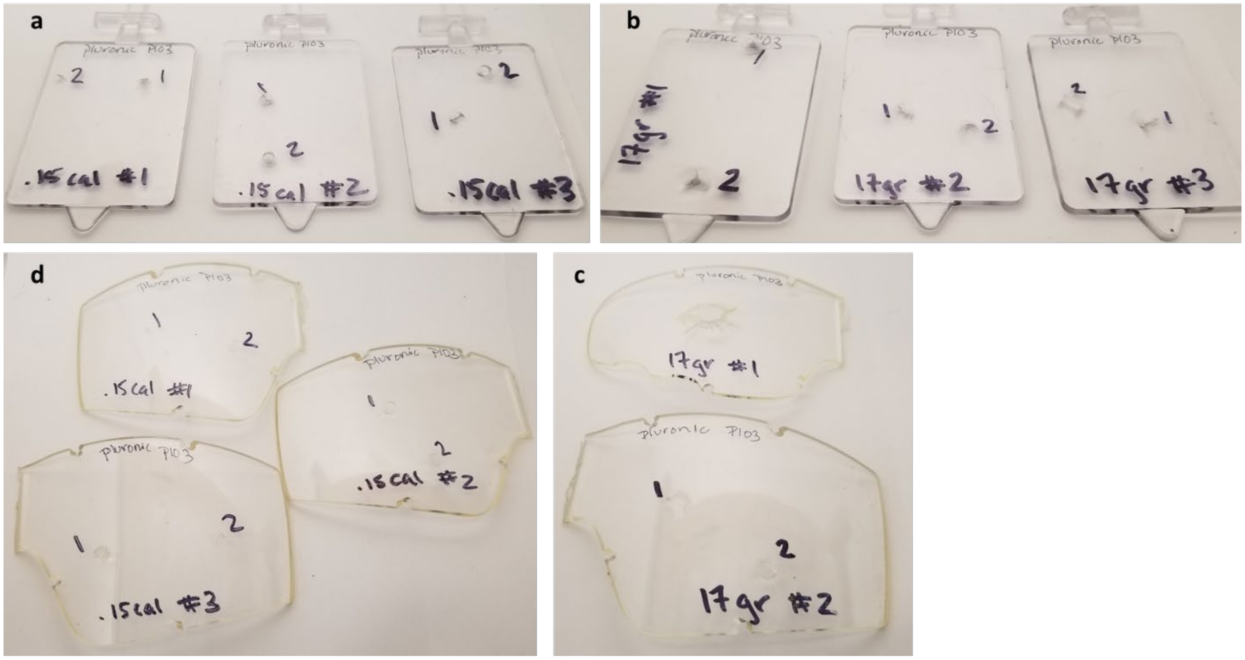

Figure A-2 – Pluronic® P103 coatings for (a) PC against 5.85 grain FSP, (b) PC against 17 grain FSP, (c) Trogamid® against 17 grain FSP, and (d) 5.85 grain FSP

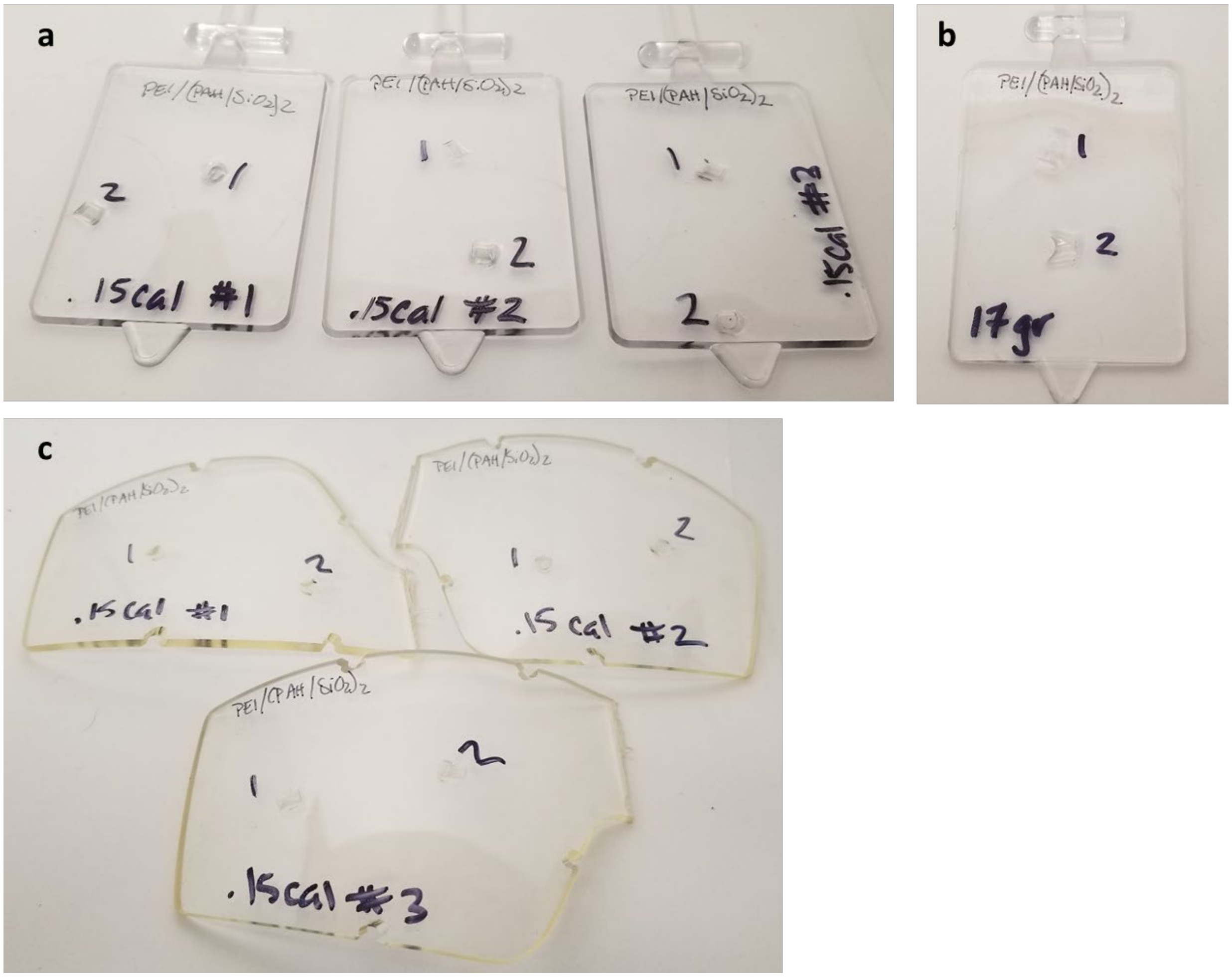

Figure A-3 - PEI/(PAH/SiO2)2 coatings on (a) PC against 5.85 grain FSP, (b) PC against 17 grain FSP, and (c) Trogamid® against 5.85 grain FSP

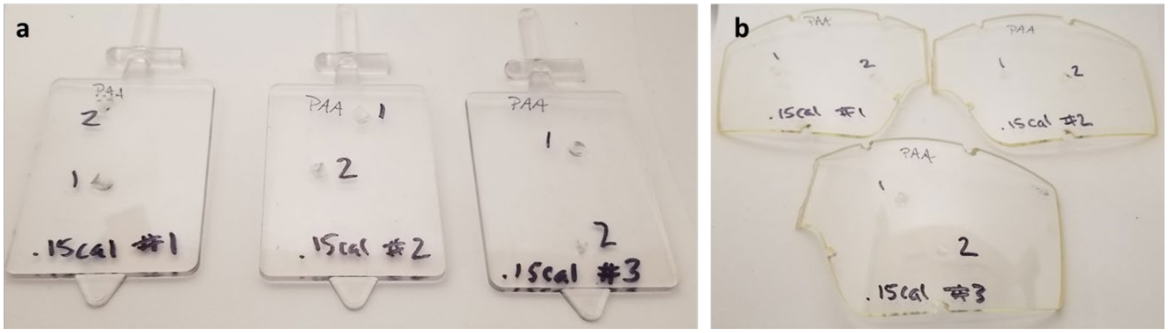

Figure A-4 - PAA coatings on (a) PC against 5.85 grain FSP and (b) Trogamid® against 5.85 grain FSP

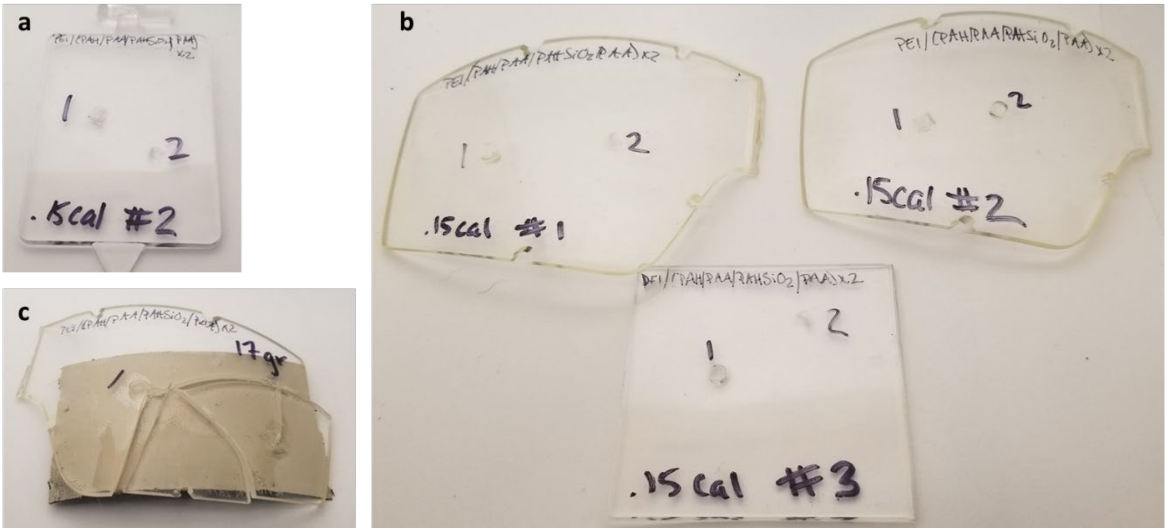

Figure A-5 - PEI/(PAH/PAA/PAHSiO2/PAA)2 coatings on (a) PC against 5.85 grain FSP, (b) Trogamid® against 5.85 grain FSP, and (c) Trogamid® against 17 grain FSP