

NATIONAL TRANSPORTATION SAFETY BOARD

Office of Research and Engineering
Materials Laboratory Division
Washington, D.C. 20594



April 2, 2020

MATERIALS LABORATORY FACTUAL REPORT

Report No. 20-011

A. ACCIDENT INFORMATION

Place : Laramie, Wyoming
Date : February 10, 2019
Vehicle : Lancair IV-P, N549CJ
NTSB No. : WPR19LA088
Investigator : Zoe Keliher, AS-WPR

B. COMPONENTS EXAMINED

Windshield pieces.

C. DETAILS OF THE EXAMINATION

An overall view of the submitted windshield pieces is shown in figure 1. Made of cast acrylic, the windshield had fractured in flight, and the middle and upper portions were missing from the recovered pieces. Each piece was examined visually, and unlabeled arrows in figure 1 indicate fracture directions determined from the visual examination. One fracture that emanated forward to aft at the left side of the windshield is labeled fracture A for reference in figure 1, and the location of the origin associated with fracture A is also indicated.

The outer edge of the windshield had a white appearance consistent with a roughening process used during the windshield installation process before bonding to the windshield frame. The bond surface on the windshield frame showed minimal visual evidence of adhesive material. An area of blue adhesive was observed on the exterior surface on the left side at the location shown in figure 1, and a closer view of the adhesive remnant is shown in figure 2. On the interior face of the windshield, circular areas consistent with epoxy resin remained in isolated areas on the bonded edge such as the forward edge near the fracture A origin as shown in figure 3. The remnants of resin had a smooth rippled appearance consistent with void surfaces.

Most of the windshield fractures had fracture planes that varied across the thickness with curving hackles turning toward the interior or exterior surface, features consistent with fracture under a combination of tension and bending loads. However, fracture A had smooth mirror-like fracture features along most of the fracture surface in a flat plane perpendicular to the interior and exterior surfaces consistent with fracture under primarily tension loads. A view of typical mirror-like fracture features away from the origin area on fracture A is shown in figure 4.

The fracture features including rib marks, hackles, and Wallner lines¹ were observed on the fracture A fracture surface emanating from an origin area located near the forward lower end of fracture A adjacent to the bonded edge as indicated in figure 4. An overall view of the fracture features at the origin area is shown in figure 5. A portion of the fracture surface had curving rib marks and with a somewhat hazy fracture surface with no evidence of Wallner lines, features consistent with preexisting progressive crack growth. A dashed line in figure 5 indicates the boundary of progressive crack growth features. The crack origin was located at the interior surface as shown in figure 5.

Closer views of the origin area are shown in figures 6 and 7. A thumbnail-shaped area had relatively smooth features with an absence of hackle features. Rib marks consistent with progressive crack growth were observed emanating from an origin area at the interior surface as indicated in figure 6. At higher magnifications as shown in figure 7, rib marks emanated from a small crack that was oriented transverse to the fracture plane. Unlabeled arrows in figure 7 indicate local crack growth directions for fracture A emanating from the small transverse crack.

Oblique views of the origin area showing the interior surface adjacent to the fracture A origin area are shown in figures 8 and 9. The surface adjacent to the fracture appeared disturbed consistent with a surface scratch. An unlabeled bracket in figure 9 indicates the area of the surface disturbed by the scratch. The transverse crack associated with the fracture A origin was located within the width of the surface scratch.

Secondary cracks were observed in the windshield to the left of the fracture A origin as shown in figure 10. The cracks were located just above the roughened bound area at the lower forward edge of the windshield, similar to the fracture A origin location. A closer view of the largest of the cracks is shown in figure 11, and reflected light was used to reveal rib markings on the crack surface. The rib markings appeared to emanate from a scratch on the interior surface of the windshield. Unlabeled arrows in figure 11 indicate several scratches observed on the interior surface above the bond line near the secondary crack.

During the course of the examination of the secondary cracks, a liquid was observed emanating from some of the secondary cracks (see figure 12). The liquid was initially dabbed with a cotton-tipped swab for analysis using Fourier-transform infrared spectroscopy (FTIR), but the sample was insufficient. After the initial sample was collected, additional liquid collected on the surface.

To facilitate both a scanning electron microscope (SEM) examination of the fracture surface and direct FTIR analysis of the liquid, the windshield was cut using a handheld bandsaw to separate the origin area from the rest of the fracture surface and to

¹ Hackles are radial features that form as a crack front diverges into different planes as a form of energy dissipation during slow or rapid fracture. Rib lines are curving features representing a crack front during slow or rapid fracture. Wallner lines are faint curving ridges on the surface that form during rapid crack growth due to crack front interactions with reflected energy waves.

cut a separate area containing a secondary crack with seeping liquid small enough to fit under the FTIR microscope for direct analysis.

The liquid from the secondary crack was analyzed using a Fourier Transform Infrared (FTIR) spectrometer with a diamond attenuated total reflectance (ATR) accessory in accordance to ASTM E1252-98 (American Society for Testing Materials E1252-98 (2013): Standard Practice for General Techniques for Obtaining Infrared Spectra for Qualitative Analysis). The spectrometer was used to collect and process infrared wavelength absorbance spectra of the unknown material(s).

The spectrum for the material contained the following combination of spectral peaks corresponding to particular functional groups found within the molecular structure of the material. The presence of two peaks $\sim 2950\text{ cm}^{-1}$ and $\sim 2920\text{ cm}^{-1}$ are indicative of a carbon-hydrogen (C-H) (aromatic) bond. The presence of a double peak at $\sim 2280\text{ cm}^{-1}$ and $\sim 2850\text{ cm}^{-1}$ is indicative of a carbon-hydrogen (C-H) (alkane) stretching bond. A peak at $\sim 1725\text{ cm}^{-1}$ is indicative of a carbon-oxygen (C=O) double bond. Peaks at $\sim 1600\text{ cm}^{-1}$ and $\sim 1580\text{ cm}^{-1}$ are indicative of an aromatic carbon-carbon (C=C) double bond. A peak at $\sim 1460\text{ cm}^{-1}$ is indicative of a carbon-hydrogen(3) (C-H₃) bending bond. A peak at $\sim 1380\text{ cm}^{-1}$ is indicative of a carbon-hydrogen(2) (C-H₂) bending bond. A series of peaks at $\sim 1270\text{ cm}^{-1}$, 1120 cm^{-1} , 1070 cm^{-1} and 1040 cm^{-1} is indicative of a carbon-oxygen-carbon (C-O-C) bond. A peak at $\sim 740\text{ cm}^{-1}$ is indicative of a carbon-hydrogen (C-H) ortho aromatic bond. A peak at $\sim 705\text{ cm}^{-1}$ is indicative of a carbon-hydrogen (C-H) meta aromatic bond. The spectrum was consistent with an ester with aromatic and straight chained groups. A spectral library search was performed on the unknown spectrum. The spectral search found a very strong match for several phthalates. Phthalates are used as plasticizers and stabilizers.

The piece of the fracture A fracture surface with the origin area was rinsed with water to remove debris from the surface followed by a rinse with ethanol and subsequent blow dry with compressed air. The fracture surface was then examined using a SEM. The SEM was operated at low voltage (1 kV) to minimize electron-beam damage to the surface, and a charge compensation device was used to minimize charge buildup on the nonconductive surface.

An overall SEM image of the origin area is shown in figure 13, and the origin area is shown at higher magnifications in figures 14 and 15. Fracture features emanated from the transverse crack as shown in figure 13, consistent with observations under optical microscopy. The surface adjacent to the origin area was spalled with surface material fractured and missing.

The fracture surface at the origin area consisted of a mix of large and small dimples as shown in figure 16. Around the surface, a series of the larger dimples connected in series, which appeared on the surface as curving tear lines that crossed and intersected each other particularly near the edge of the fracture adjacent to the windshield interior surface. A close view of one of these tear lines is shown in figure 17. Rib marks were also observed near the origin area as shown in figure 18. A tear line in figure 18 is shown

intersecting the rib marks at this location. Overall, the appearance of the fracture surface at the origin area was consistent with environmental stress cracking (ESC). ESC is a fracture mechanism in polymer materials that occurs when a susceptible polymer material is exposed to a combination of tensile stress and exposure to a substance that degrades the integrity of the material.

A piece of the windshield from the upper aft area away from the origin was cut into a rectangular shape, and the interior surface was scratched with a razor blade. Next, one end of the rectangular section was placed in a vice, and the opposite end was struck with a mallet to produce a bending impact fracture initiating from the surface scratch. An overall optical image of the resulting lab-induced fracture is shown in figure 19, and a closer view of the origin area is shown in figure 20. The origin area appeared relatively smooth, and parabolic marks were observed near the origin as shown in figure 20.

The lab-fractured piece was further examined using an SEM, and resulting images of the origin area are shown in figures 21 and 22. The origin area showed feathery features with tear ridges consistent with microductility associated with the fracture.

Matthew R. Fox, Ph.D.
Senior Materials Engineer

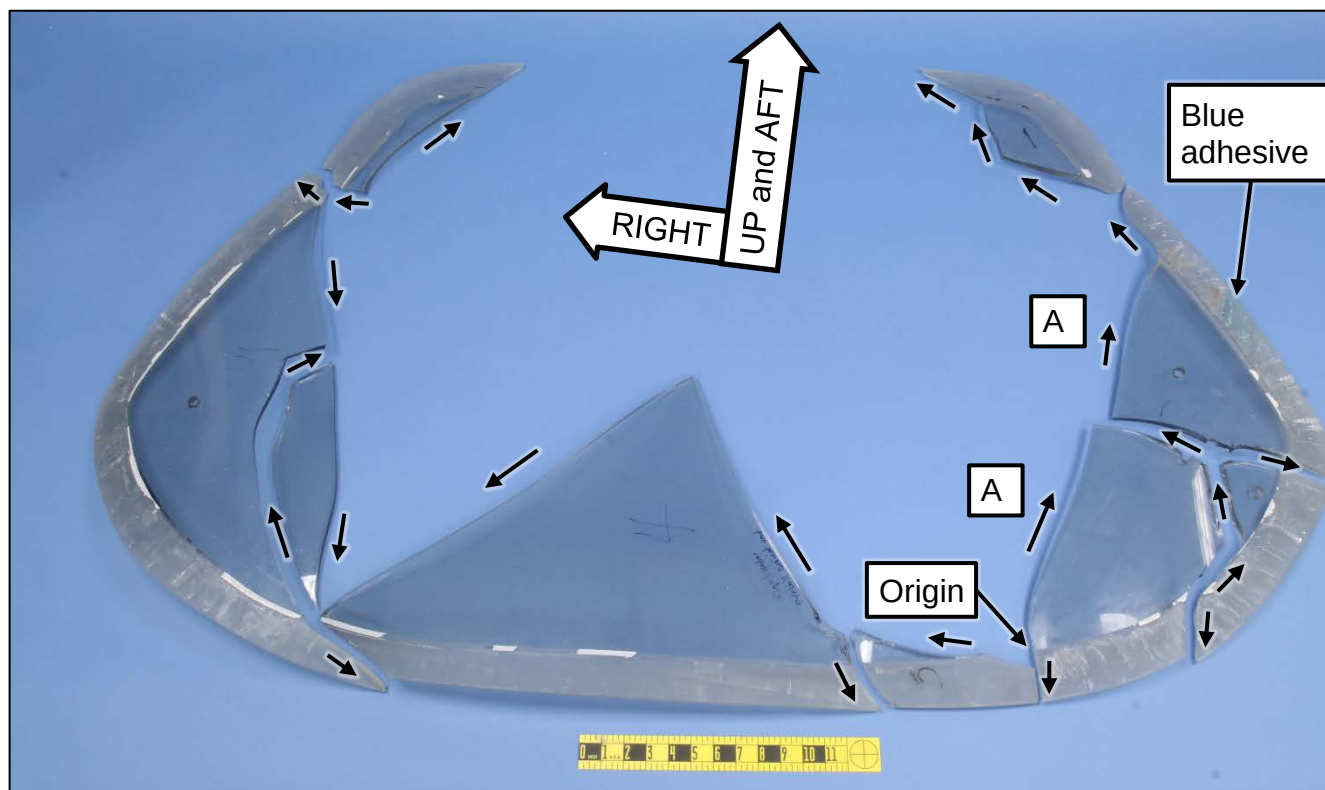


Figure 1. Overall view of the submitted windshield pieces. Unlabeled arrows indicate fracture propagation directions.

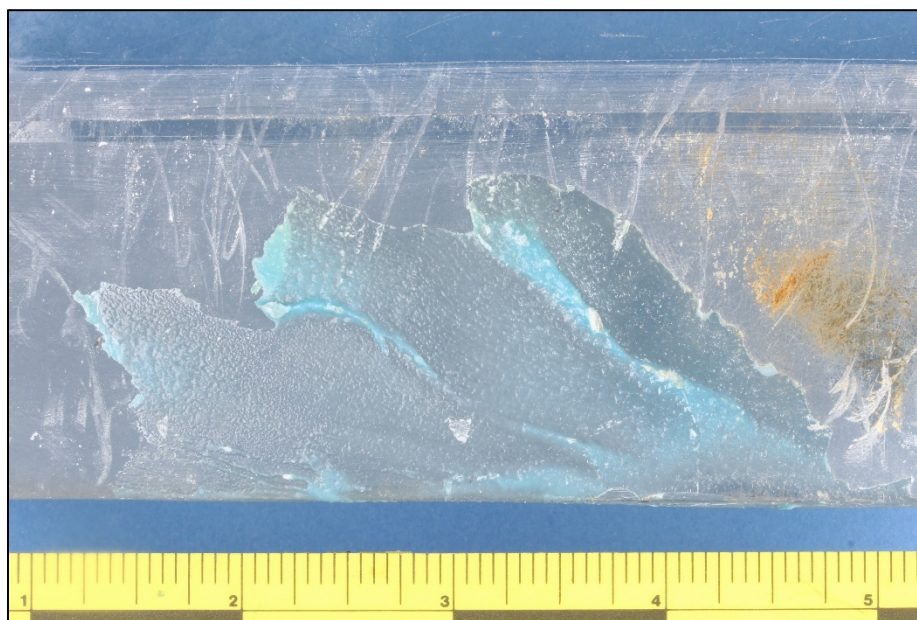


Figure 2. Area of blue adhesive on the exterior surface of the bond area on the left side of the windshield.

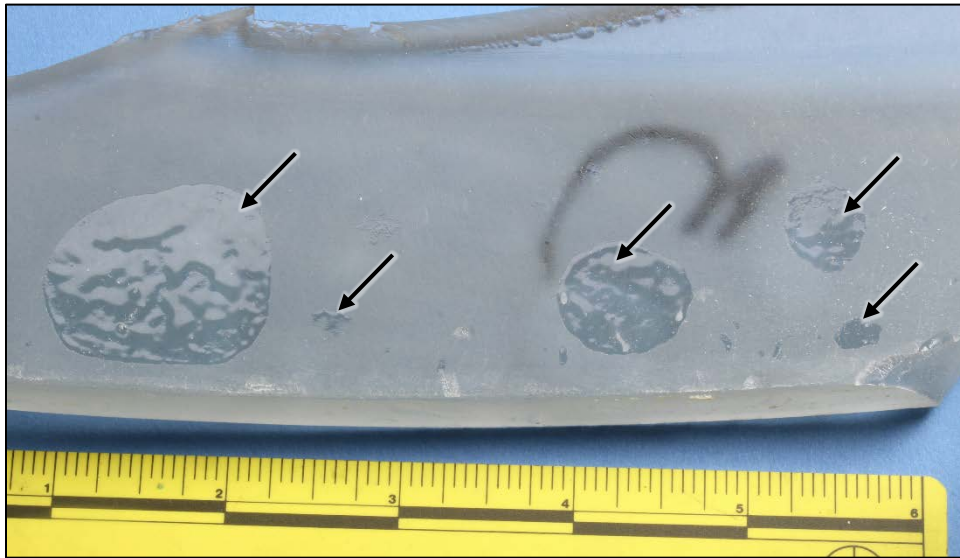


Figure 3. Areas of epoxy on the interior surface of the bond area at the lower forward edge of the windshield.

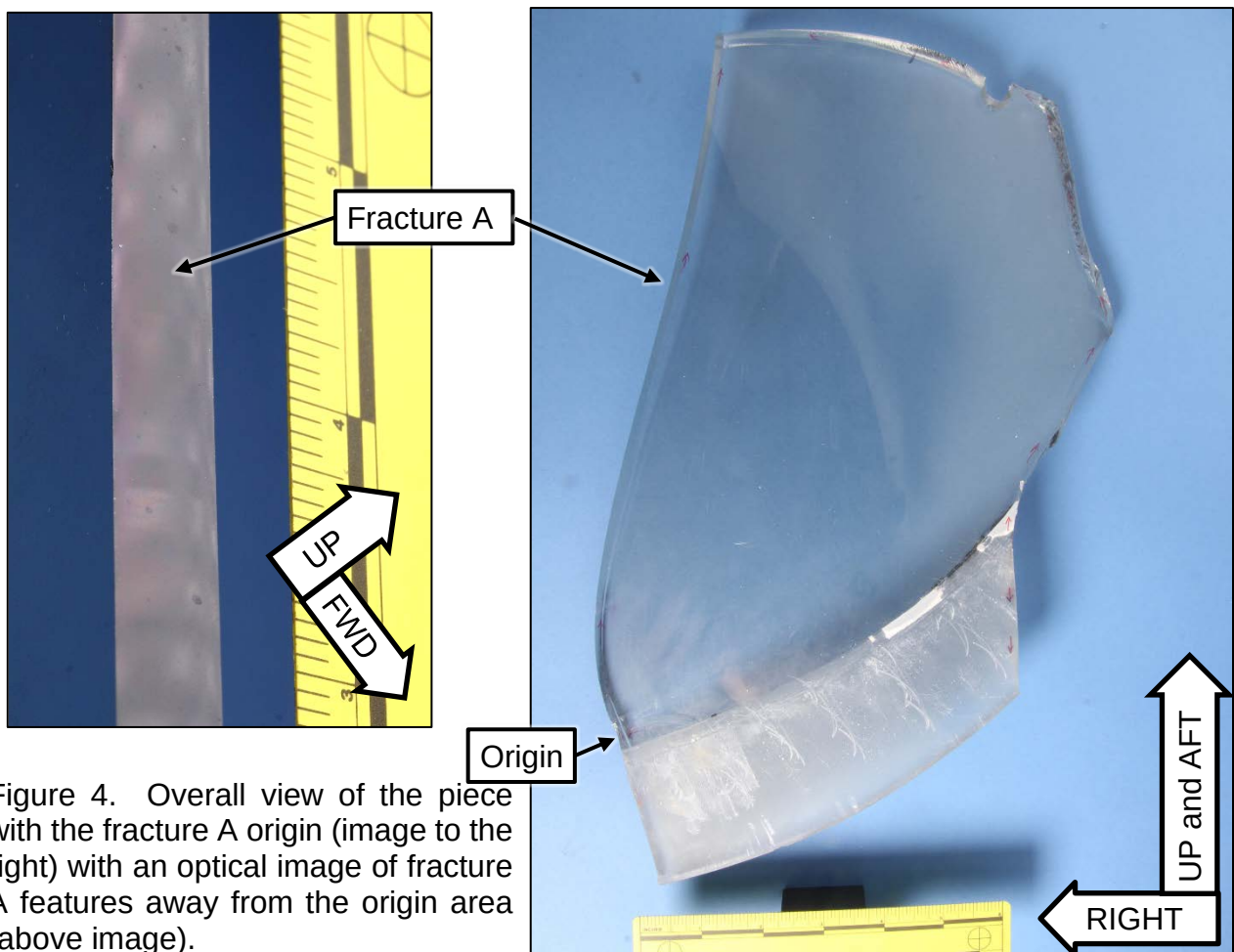


Figure 4. Overall view of the piece with the fracture A origin (image to the right) with an optical image of fracture A features away from the origin area (above image).

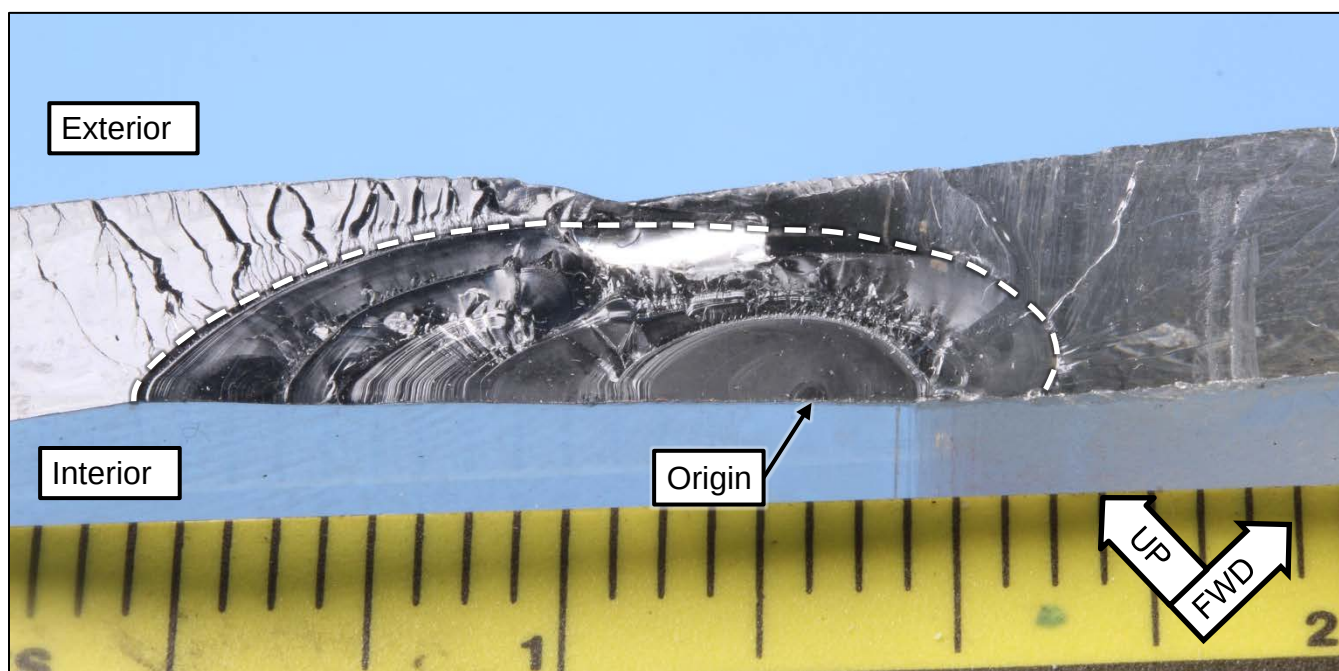


Figure 5. Optical image of fracture features at the origin of fracture A. A dashed line indicates the boundary of features consistent with progressive crack growth.

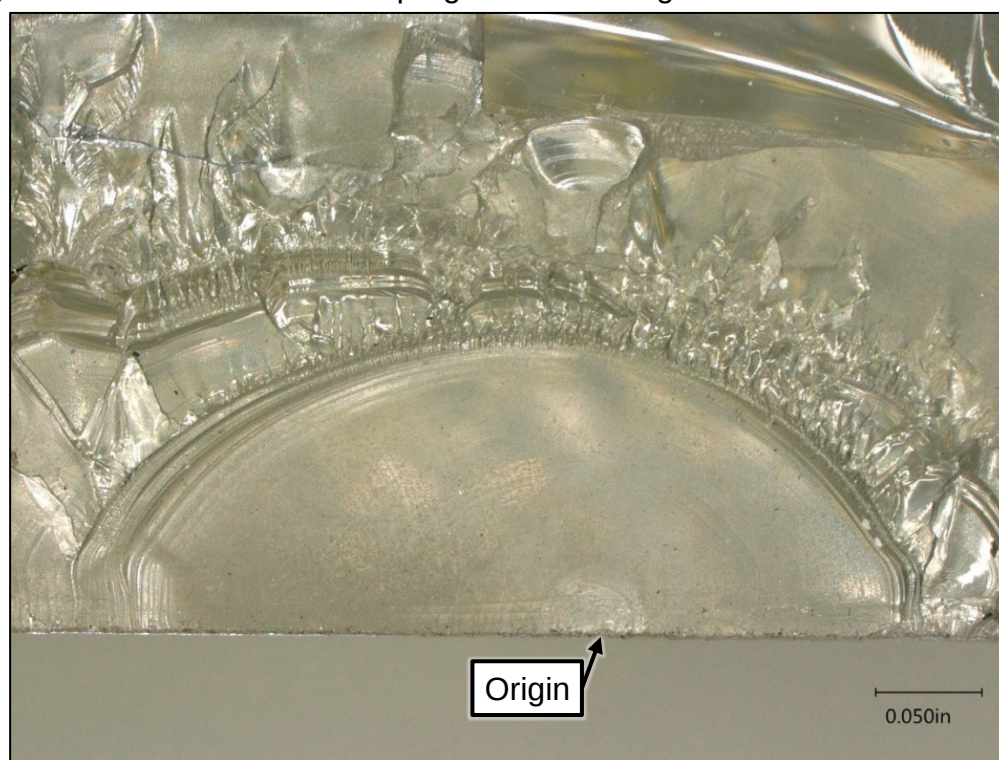


Figure 6. Optical image of the origin area at higher magnification.

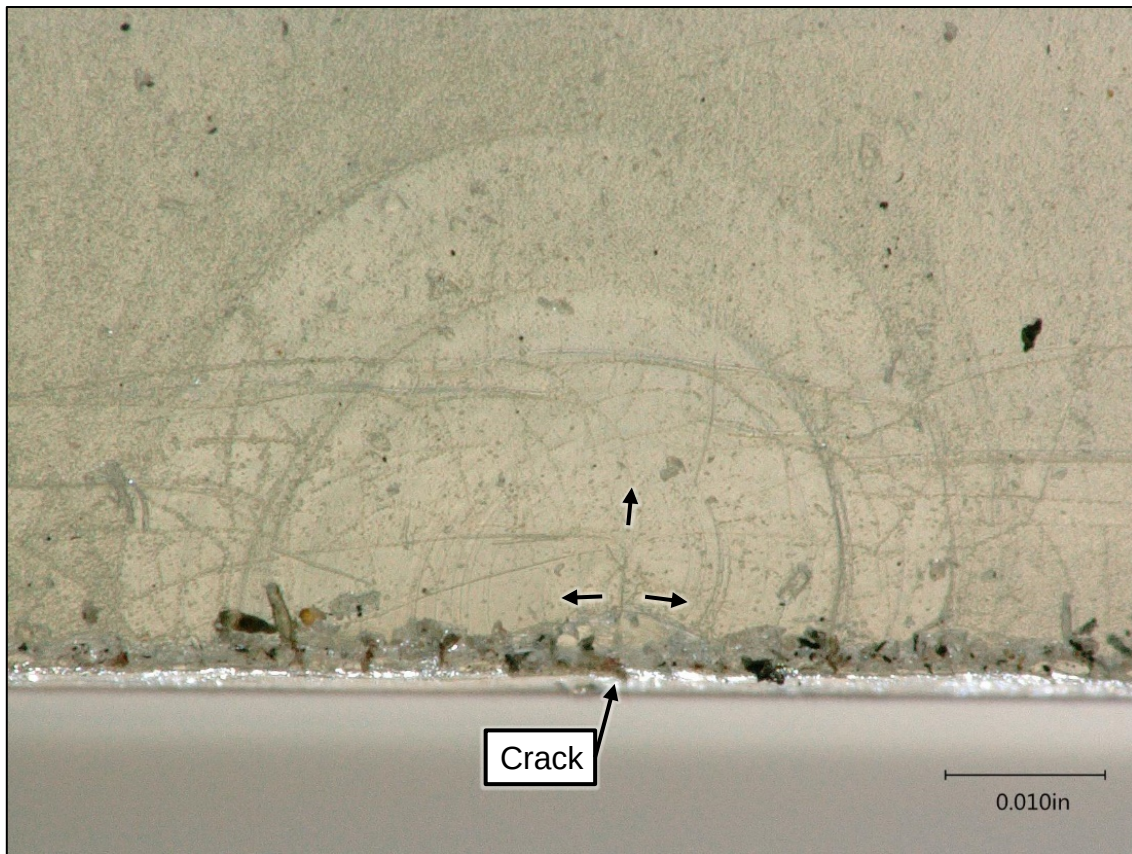


Figure 7. Optical image of the fracture A origin at higher magnification. Unlabeled arrows indicate local directions of crack growth emanating from a surface crack oriented perpendicular to fracture A.

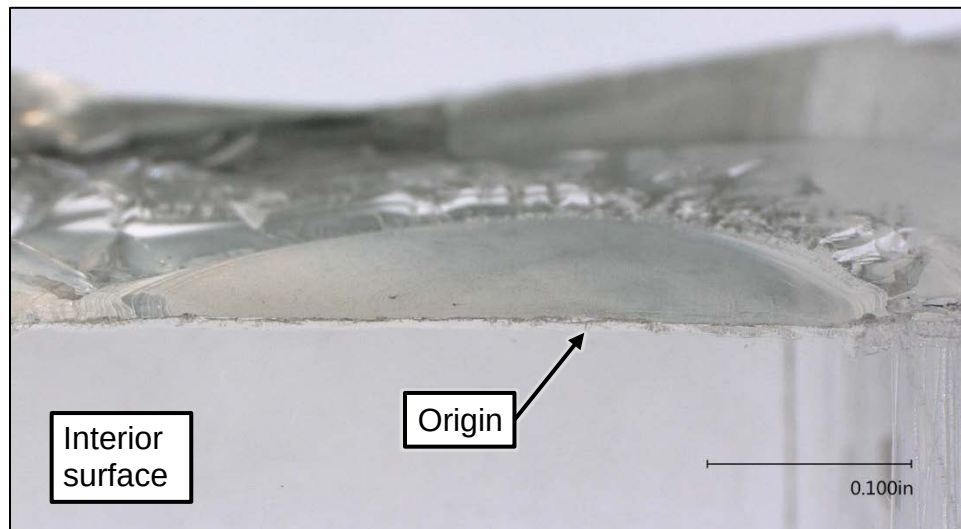


Figure 8. Oblique view of the fracture A origin area.

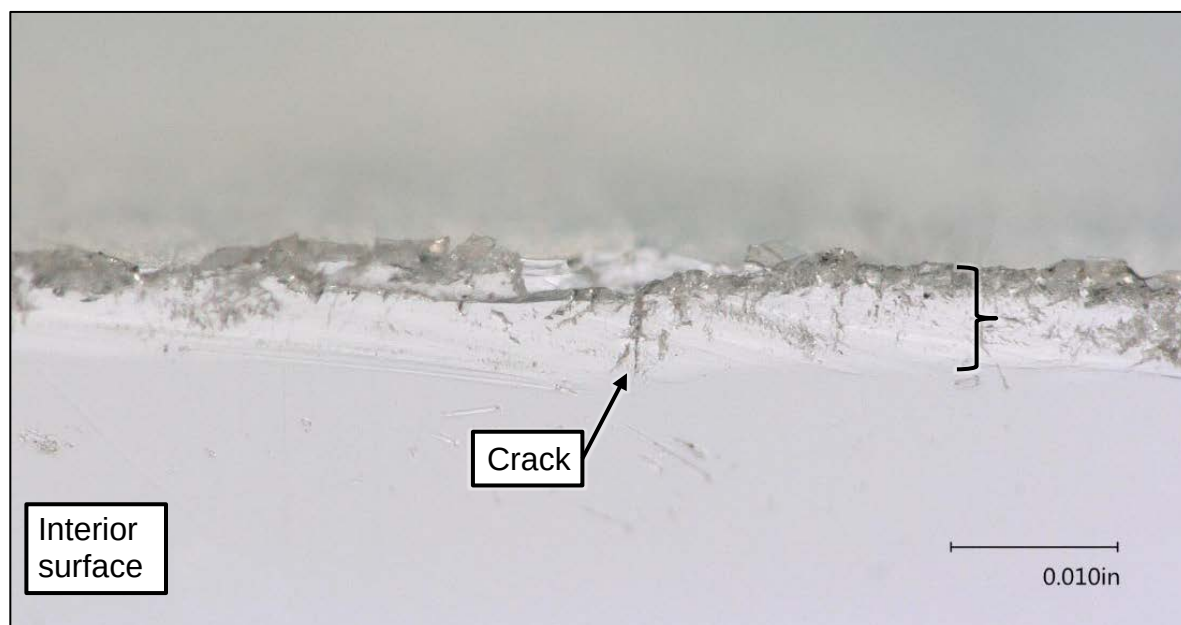


Figure 9. Interior surface of the windshield adjacent to fracture A where the transverse crack associated with the fracture origin is indicated. An unlabeled bracket indicates an area of disturbed surface adjacent to the fracture surface.

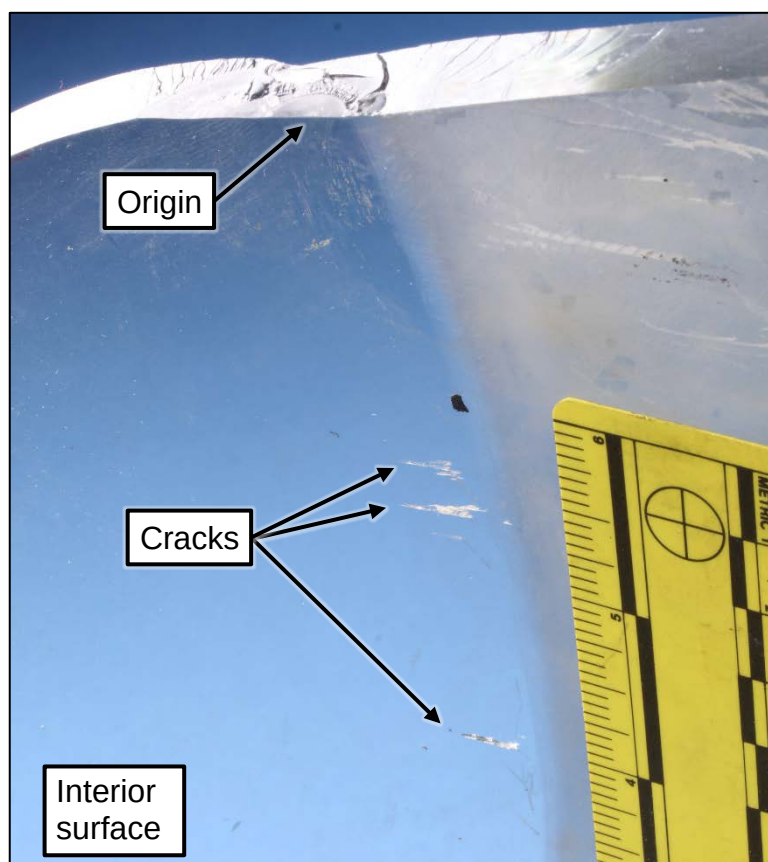


Figure 10. Interior surface of the windshield adjacent to fracture A showing additional cracks located just above the bondline.

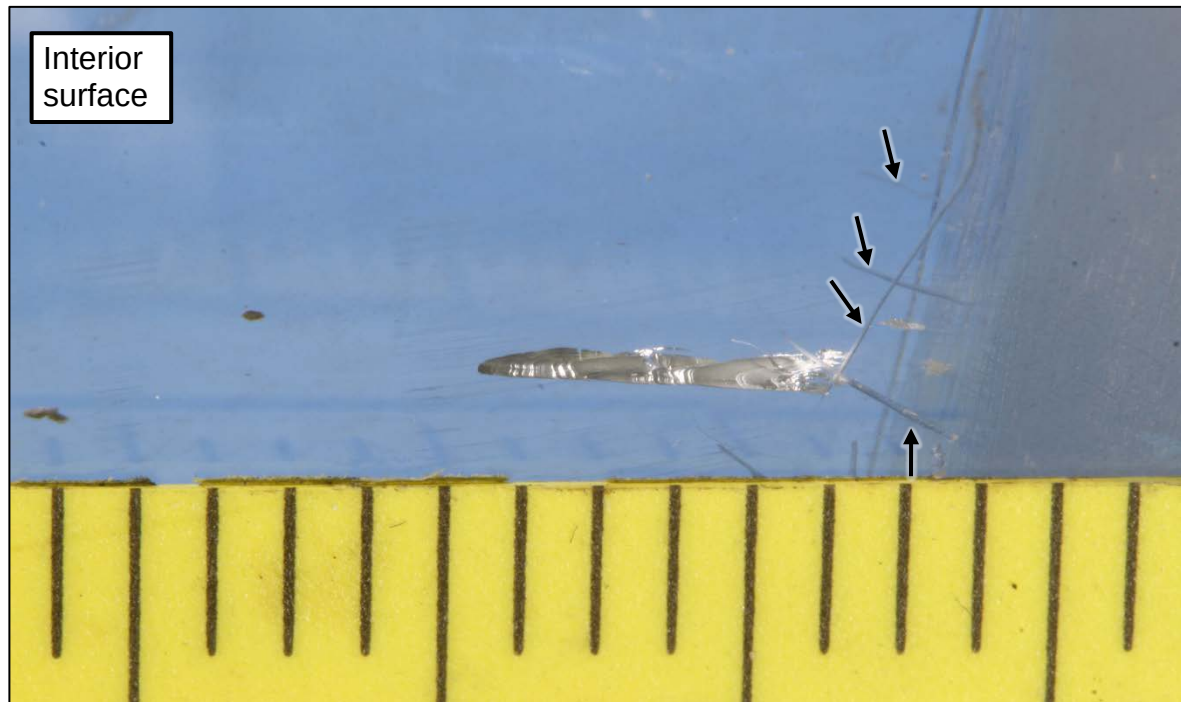


Figure 11. Closer view of one of the cracks shown in the previous figure. Unlabeled arrows indicate scratches on the interior surface, one of which appeared to coincide with the crack origin.

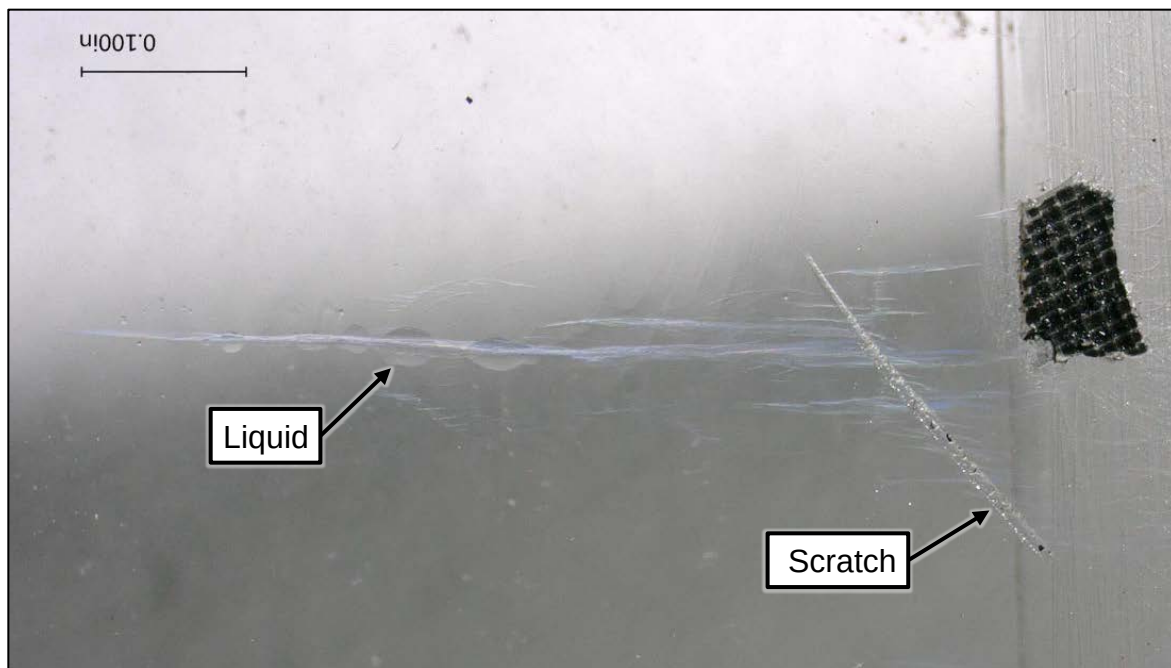


Figure 12. Additional cracks adjacent to the bondline in the vicinity of a scratch. Liquid was noted oozing from one of the cracks.

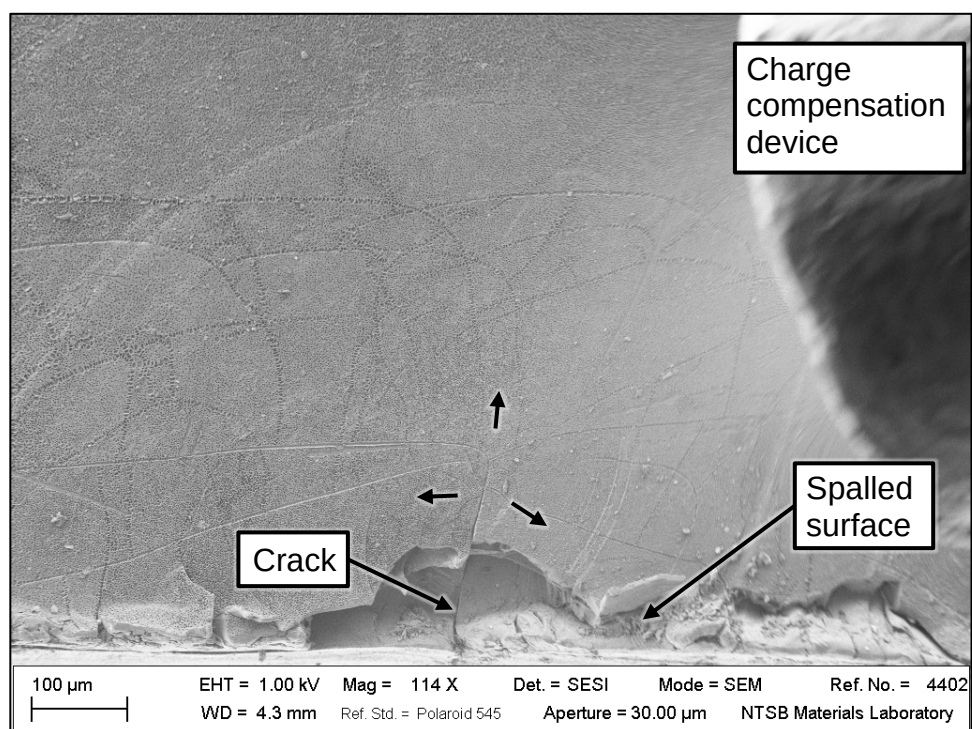


Figure 13. SEM image of the crack A origin area.

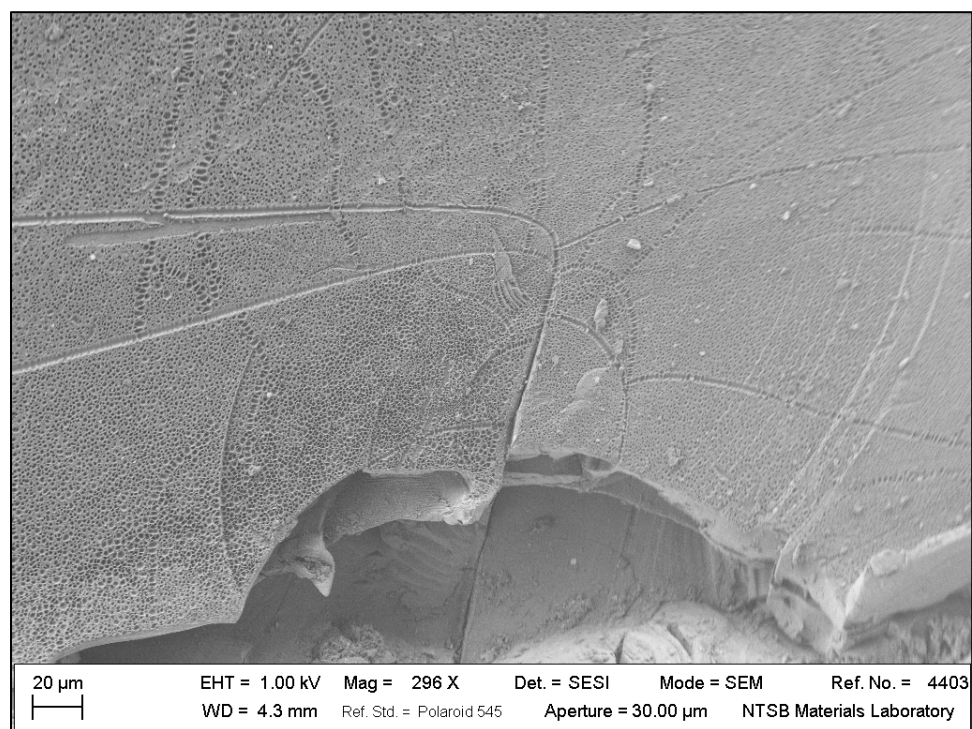


Figure 14. SEM image of the fracture A origin area at higher magnification.

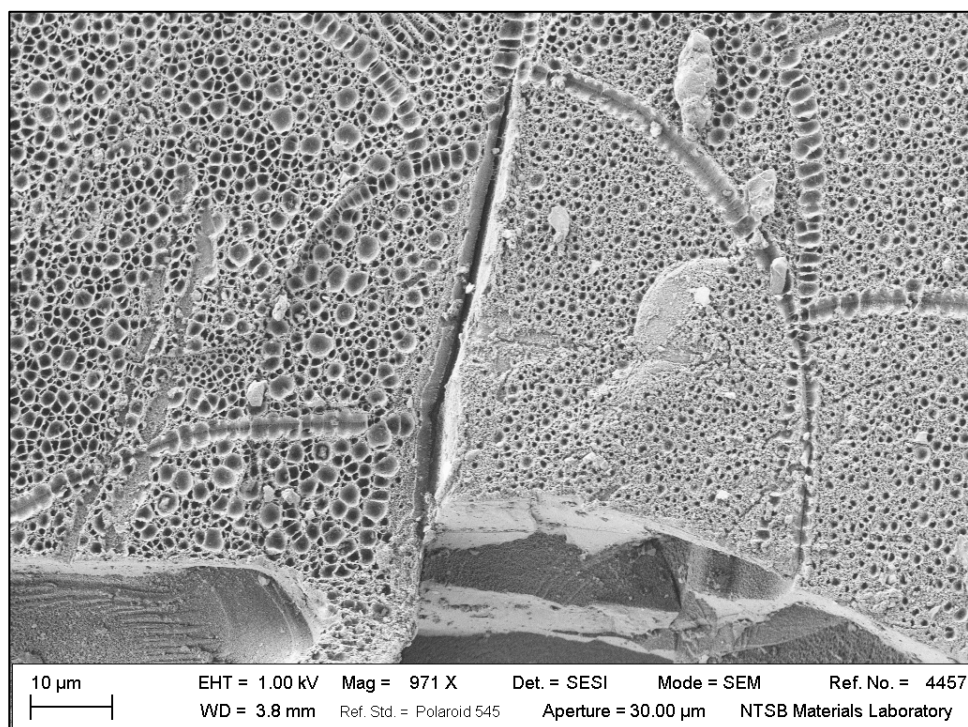


Figure 15. SEM image of the fracture A origin area at higher magnification.

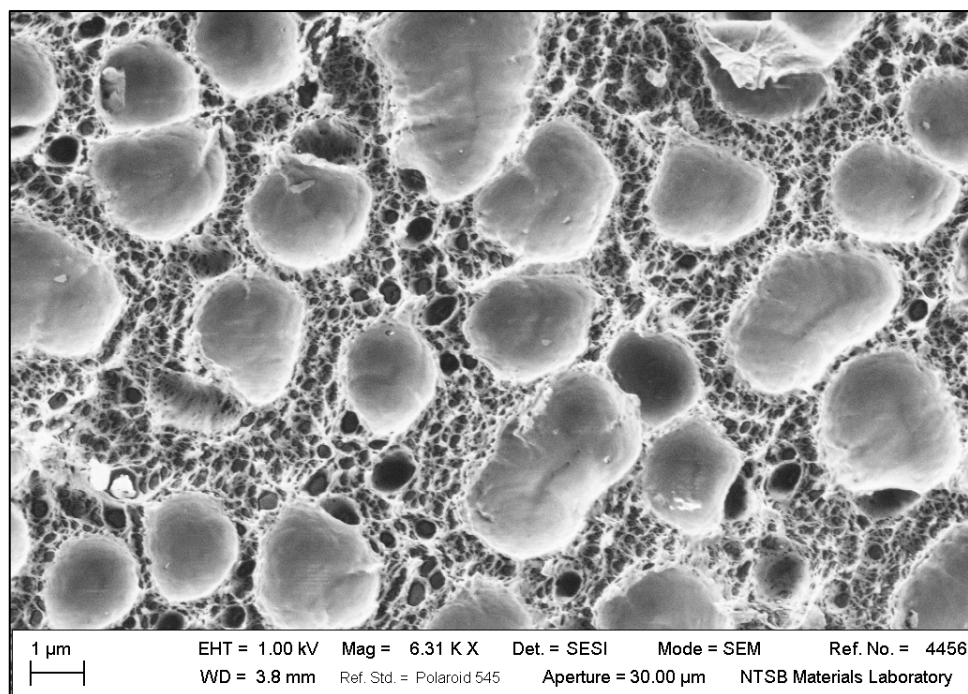


Figure 16. SEM image of fracture features near the fracture A origin area.

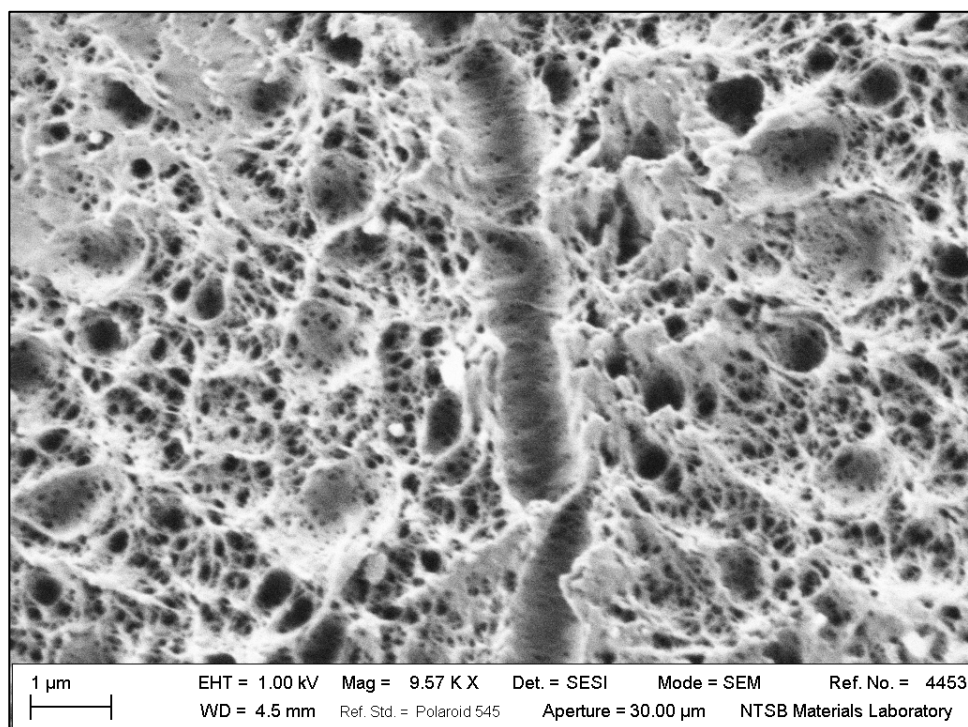


Figure 17. SEM image of a tear line near the fracture A origin.

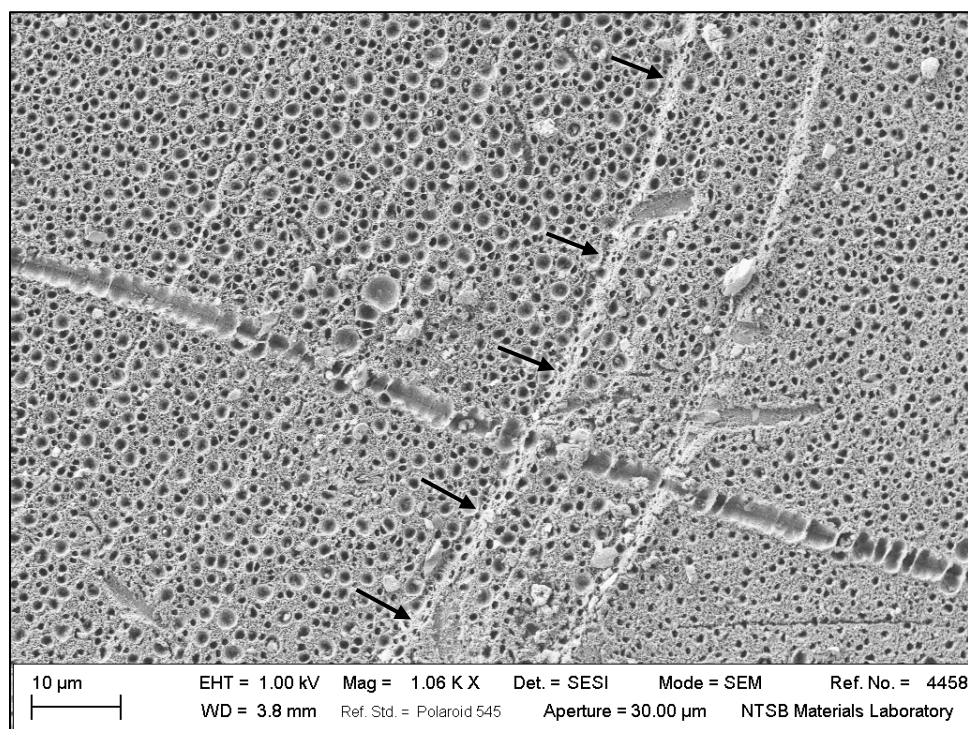


Figure 18. SEM image of a tear line and rib marks near the fracture A origin. Unlabeled arrows point to one of the rib marks.

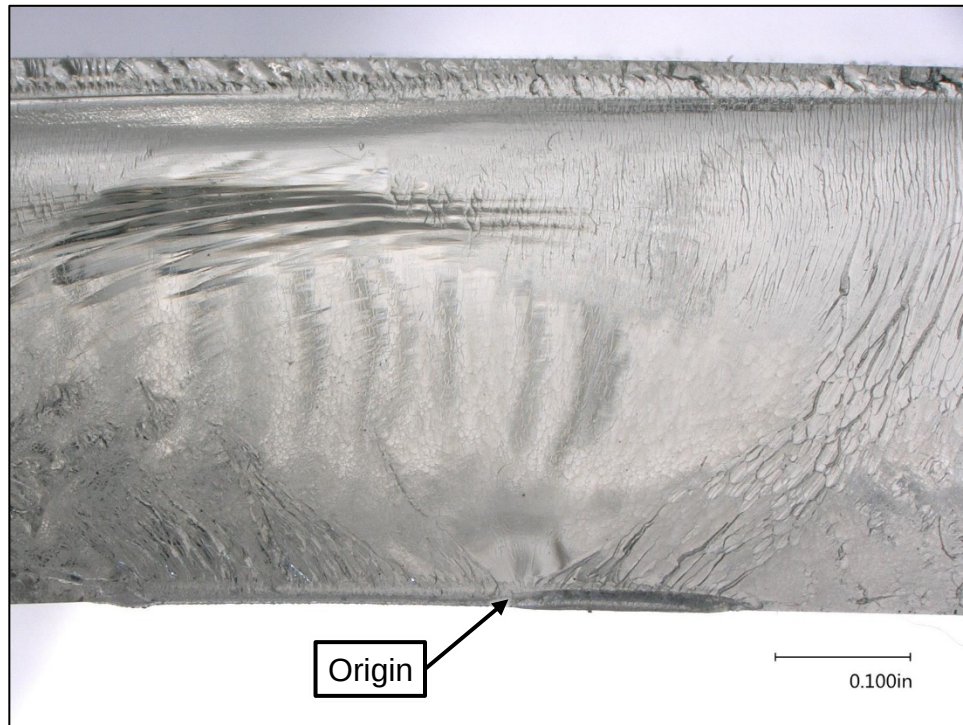


Figure 19. Overall optical image of the origin area of a windshield piece that was scored then fractured by impact in the lab.

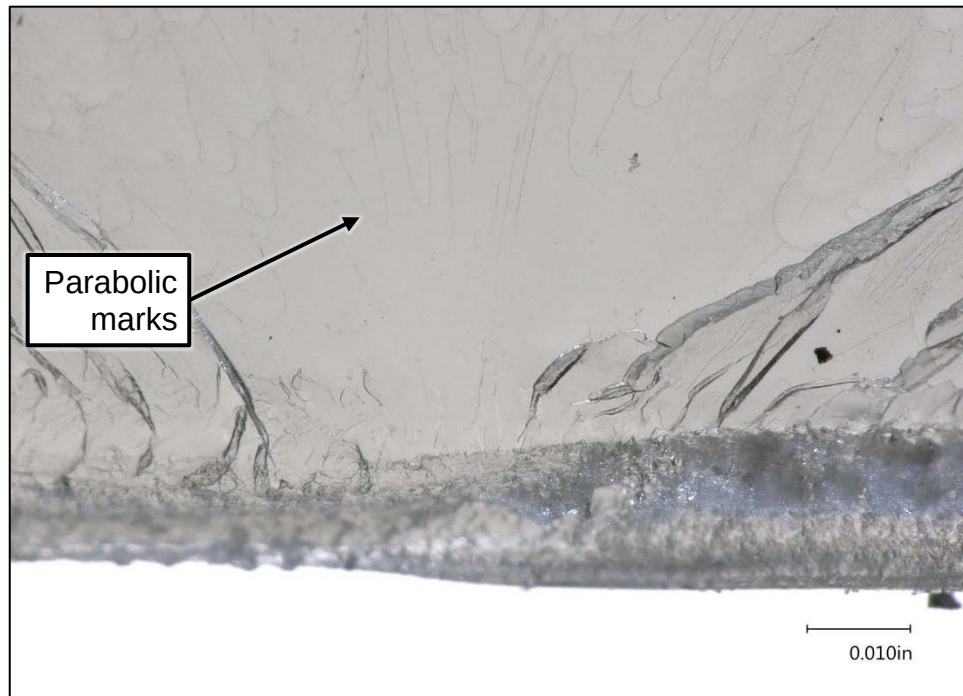


Figure 20. Closer optical image of the origin area of the lab-induced impact fracture.

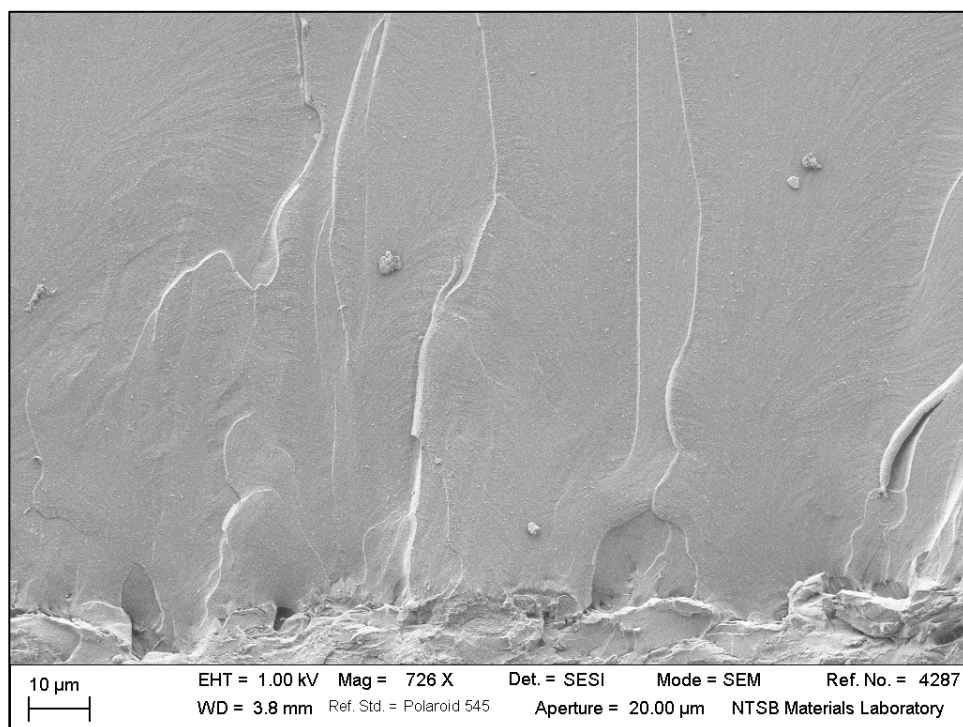


Figure 21. SEM image of the origin area of the lab-induced impact fracture.

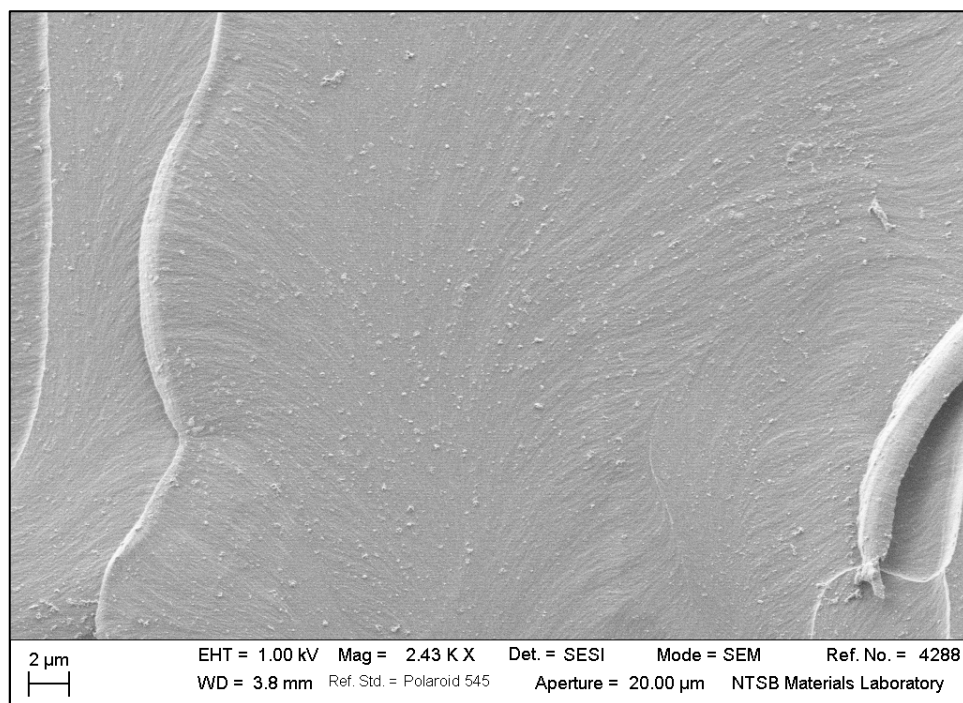


Figure 22. SEM image of feathery features near the origin area of the lab-induced impact fracture.