

National Transportation Safety Board

Office of Research and Engineering

Washington, DC 20594



WPR22LA019

MATERIALS LABORATORY

Specialist's Factual Report 22-066

September 22, 2022

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A. ACCIDENT INFORMATION

Location: Fall Creek, Oregon
Date: October 14, 2021
Time: 18:15 Pacific daylight time
11:15 coordinated universal time
Vehicle: Lancair ES, N511ZZ
Investigator: Andrew Swick, AS-WPR

B. COMPONENTS EXAMINED

Camshaft gear remnant
Remnants of gear teeth
Worn gear debris

C. EXAMINATION PARTICIPANTS

Specialist Erik Mueller, Ph.D., P.E.
Office of Research and Engineering – Materials Laboratory Division
NTSB

D. DETAILS OF THE EXAMINATION

On October 14, 2021, about 1815 Pacific daylight time, an experimental amateur built Lancair ES was substantially damaged when it was involved in an accident near Fall Creek, OR. The pilot was not injured. According to the pilot, the engine decelerated and misfired during flight, with attempts at restarting the engine unsuccessful, as smoke began to enter the cockpit. The pilot deployed the ballistic recovery system parachute, and the airplane collided with trees, resulting in separation of the empennage. The wreckage was relocated to a secured facility for further examination.

Figure 1 and Figure 2 show the camshaft gear remnant, as submitted. The markings written on the gear face stated "631845-F," with indelible ink markings stating, "631845." Thirty-six of the teeth had fractured and liberated from the gear. Twenty-four of the teeth were still intact and relatively undamaged, and one tooth was intact but deformed on the top land and forward face. Of these fractured gear teeth, only six still exhibited fracture features, as exemplified in the cluster shown in Figure 3. The remainder had been obliterated or destroyed, consistent with post-fracture damage to the gear. This damage was enough to completely smooth over most of the fracture sites.

Five of the teeth that had liberated from the camshaft gear had been recovered and were received by the NTSB Materials Laboratory, as illustrated in Figure 4. The gear teeth were arbitrarily numbered 1 through 5, for the purposes of this report.

Figure 5 shows the fractured gear tooth #1, from the side and the fracture surface. The fracture surface exhibited a sloping, angled orientation, whose edges were located along the fillet radius below the flank. The fracture surface itself was mottled and reflective, consistent with post-fracture smearing. Examination of gear teeth #2 and #5 revealed similar features (the fracture surfaces of these teeth were not included in this report).

Figure 6 shows the fracture surface and side of the fracture surface edge of gear tooth #3. While also exhibiting an angled appearance, the fracture surface exhibited two areas with distinct features. The lower area in Figure 6a exhibited concentric marks consistent with crack arrest marks. The edge exhibited perpendicular features consistent with ratchet marks. These features were consistent with propagation of a pre-existing crack.

The #3 tooth was examined using a field-emission scanning electron microscope (SEM). Figure 7 shows a typical area of the fracture surface region with crack arrest marks—this area exhibited striations, consistent with fatigue crack propagation. Outside of this area on the fracture surface (or the upper area in Figure 6a), the fracture surface exhibited slanted dimpled rupture (Figure 8). These features were consistent with overstress fracture in shear. The fracture characteristics were consistent with this gear tooth having fractured from a fatigue crack that propagated about halfway through the tooth cross section before the remainder fractured in overstress.

The initiation area of the fatigue crack is shown from the edge in Figure 9. As described previously, this area exhibited ratchet marks, consistent with multiple fatigue crack initiation sites. A planar view of one of these sites, located between two ratchet marks, is shown in Figure 10. Even after cleaning, many of the initiation sites retained post-fracture contamination, and several had been damaged by impacts and smearing. Figure 11 shows one undamaged initiation site. Located along the fillet radius of the tooth, the initiation site exhibited several concentric convex features, consistent with emanating or propagating from the surface site. A surface region 20 to 30 μm (7.9 to 11.8×10^{-4} inch) thick was present along the fracture surface edge. This area exhibited a flatter surface texture.

Another fatigue crack initiation site from this gear tooth, just left of a ratchet mark, is shown in Figure 13. Figure 14 shows a closer view of this site. Examination found a relatively flat edge, but there was some undulation along the surface, consistent with the surface wear marks along vertically oriented smearing lines (lower half of Figure 14). The radial lines on the fracture surface were consistent with crack propagation

away from this region. There was also some surface material present on the fillet surface of the fracture tooth, consistent with contamination.

Gear tooth #4 also exhibited comparable features to gear tooth #3. As illustrated in Figure 15, gear tooth #4 exhibited concentric crack arrest marks over much of the fracture surface. Examination using a SEM found striations in this region, consistent with fatigue crack propagation. Outside this area (upper portion of Figure 15a), dimpled rupture was observed. Like the #3 fractured tooth, the #4 tooth exhibited a fatigue crack that propagated through over half the cross section, followed by the remaining material fracturing from overstress.

The initiation area, shown visually in Figure 17, was collocated at a fillet radius between the bottom land and the flank. Unlike tooth #3, there appeared to be only one initiation site for the fatigue crack of gear tooth #4. This was exemplified by the absence of ratchet marks (see Figure 18). As shown along and below the edge of the fracture surface in Figure 18, the crack initiation site was collocated with a gouge or machine mark.

Figure 19 shows a closer view of the fatigue crack initiation site. This location showed the river patterns emanating outward away from the surface, consistent with the crack propagation direction into the thread material. There was also a surface area parallel to the fracture edge, which exhibited a flatter morphology than the radiating surface features further inward. The thickness of this layer was consistent with that of gear tooth #3 (shown in Figure 12 and Figure 14).

The fractured tooth #1 was mounted, polished, and etched with a 2% Nital solution to examine the camshaft gear teeth microstructure.¹ The grain flow of the material conformed to the shape of the threads, consistent with the forging manufacture of the camshaft gear. Figure 20 shows a typical area of the gear tooth microstructure, towards the central core location. The microstructure exhibited a morphology consistent with tempered martensite, exhibiting acicular lighter ferrite phases and cementite-containing darker constituents. This microstructure was typical for alloy steels having been quenched and tempered after normalizing or annealing.

The edge of the cross-sectioned tooth #1 near the fracture surface is illustrated in Figure 21. The fracture surface itself had been smeared to the extent that the fracture features were obliterated, and as such, the surface exhibited rounding along the microstructural features. However, approximately 0.001 inches above the fracture surface, (to the right in the figure) a parallel secondary crack was observed. This crack extended approximately 0.006 inches into the tooth.

¹ Nital - a mixture of 2% concentrated nitric acid (HNO₃) in ethanol (C₂H₅OH).

A similar crack was found on the opposite side of the tooth away from the fracture surface. As shown in Figure 22, this crack was approximately 0.007 inches long, and it had initiated at the surface. In both cases, the cracks were oriented perpendicular to the surface, consistent with transgranular propagation.

The composition of the gear was examined using energy dispersive x-ray spectroscopy (EDS) and x-ray fluorescence (XRF). The chemical composition was consistent with an alloy steel. As shown in the micrographs, the gears exhibited a surface layer with a lighter contrast. Examination of this surface layer with EDS found it to contain nitrogen, consistent with a nitride surface treatment. The hardness of the tooth cross section was inspected with a microindentation hardness tester per ASTM E384.² The hardness of the base alloy exhibited a hardness of 41 HRC (401 HV₅₀₀). The hardness data and microstructure were consistent with a quench and tempered condition for this alloy composition.

Submitted by:



Erik M. Mueller
Materials Research Engineer

² ASTM E384 - *Standard Test Method for Knoop and Vickers Hardness of Materials*. ASTM International, West Conshohocken, PA

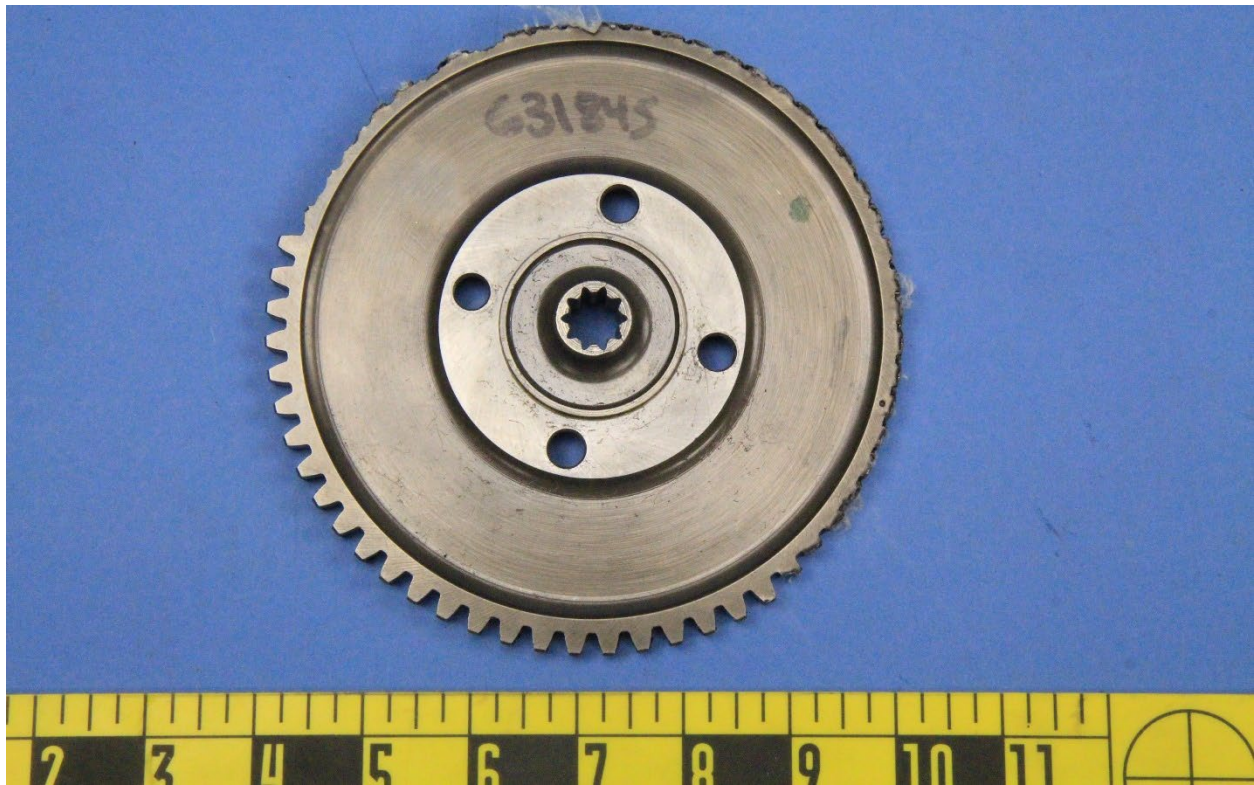


Figure 1. View of the forward face of the camshaft gear, as received.

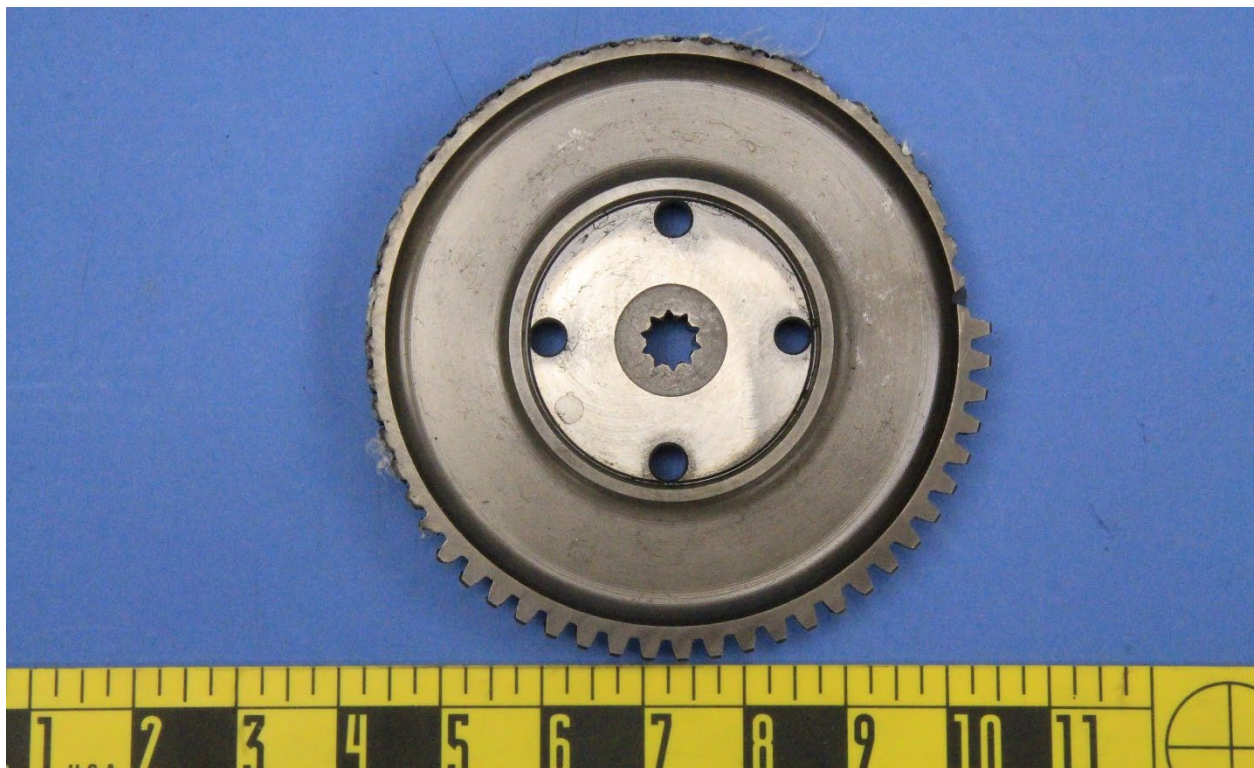


Figure 2. View of the aft face of the camshaft gear, as received.

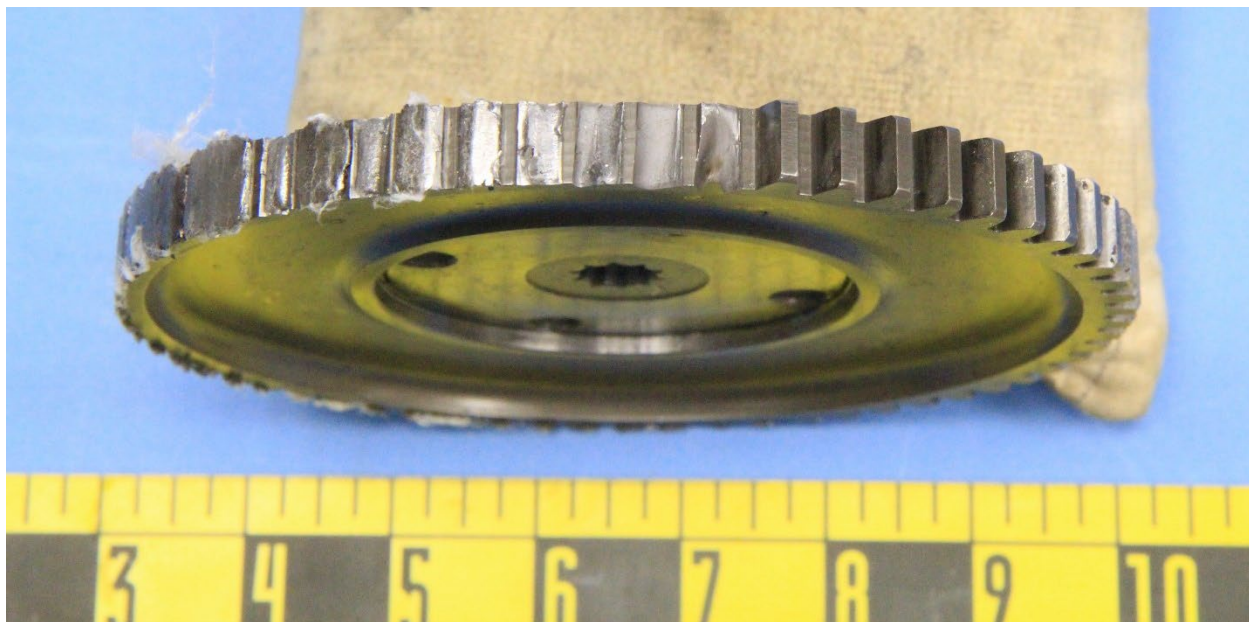


Figure 3. View of the fractured teeth on the camshaft gear.

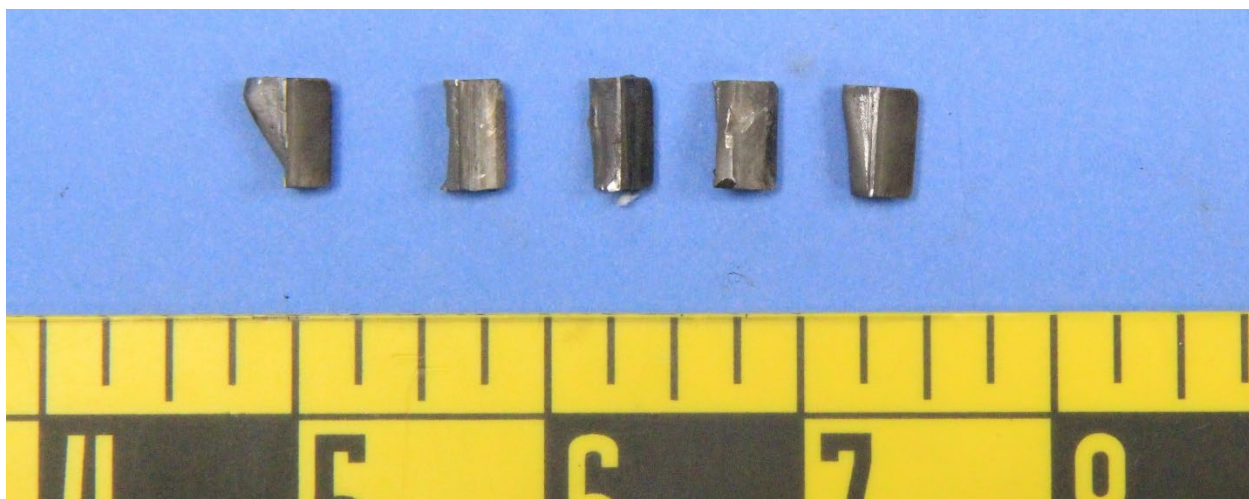


Figure 4. Five of the liberated camshaft gear teeth recovered from the engine, as received.

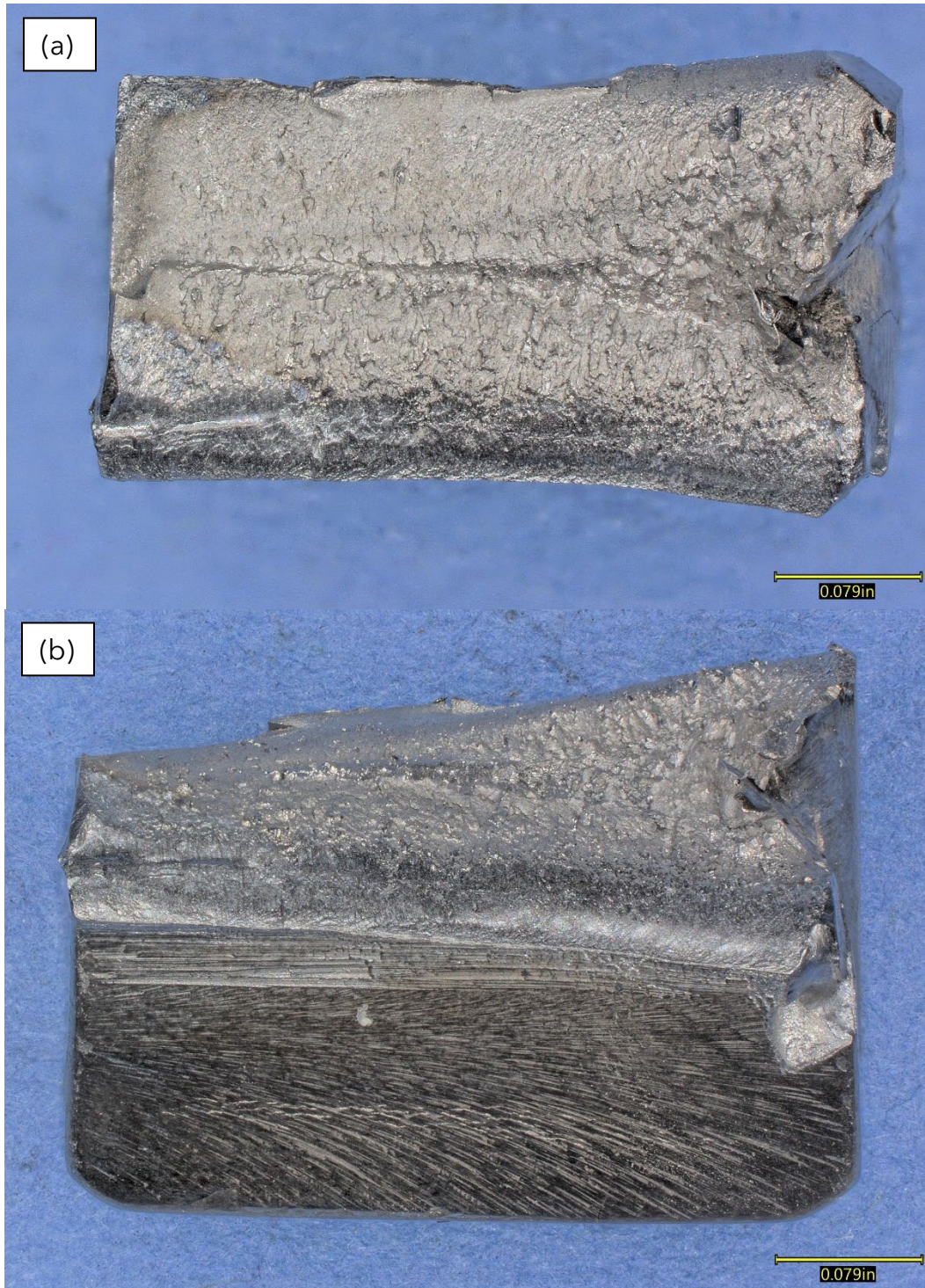


Figure 5. Views of the fractured gear tooth #1, viewed from (a) the fracture surface and (b) the side.

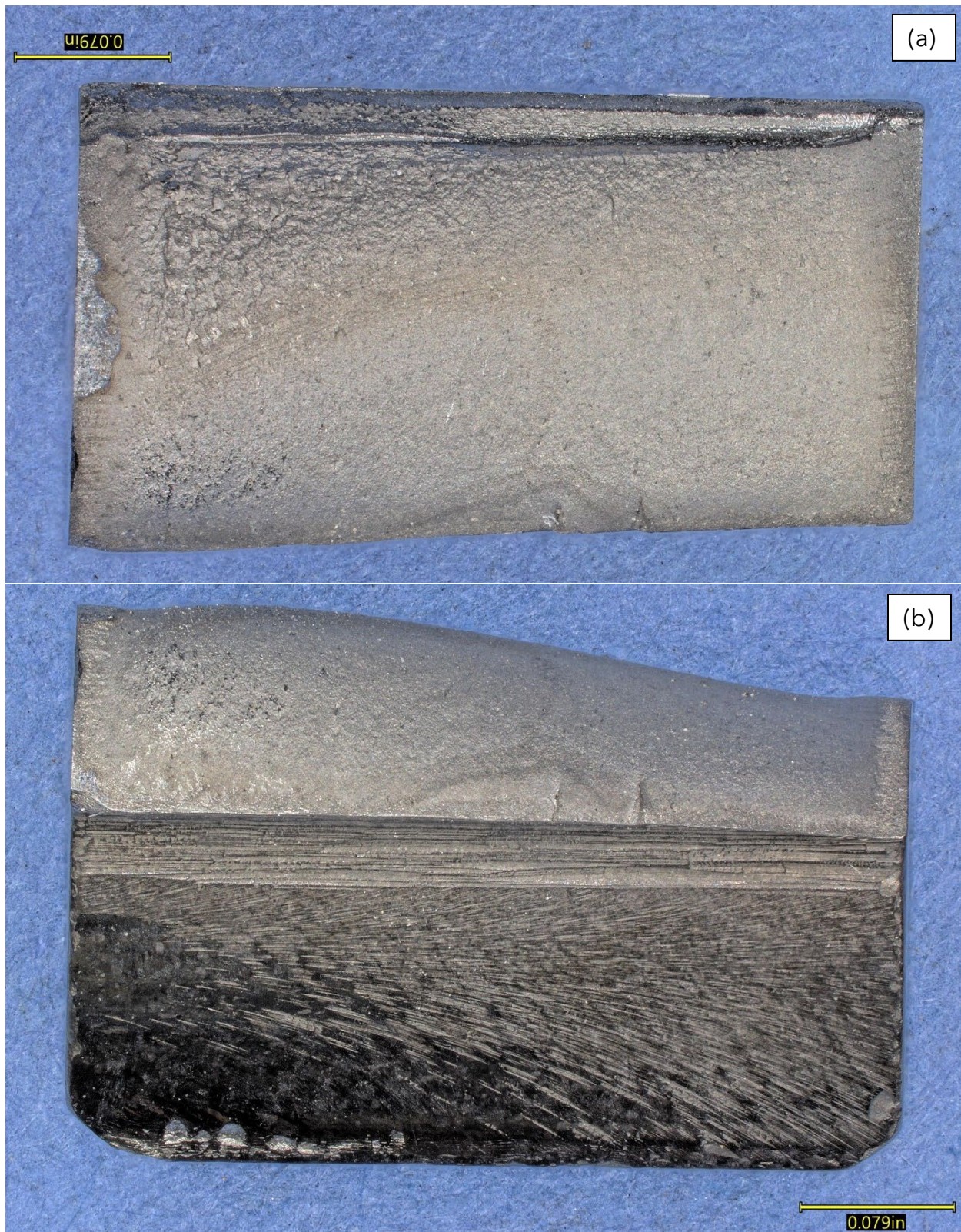


Figure 6. Views of the fractured gear tooth #3, from (a) the fracture surface and (b) the side of crack initiation. The figures are annotated to show the crack propagation direction and crack initiation site(s).

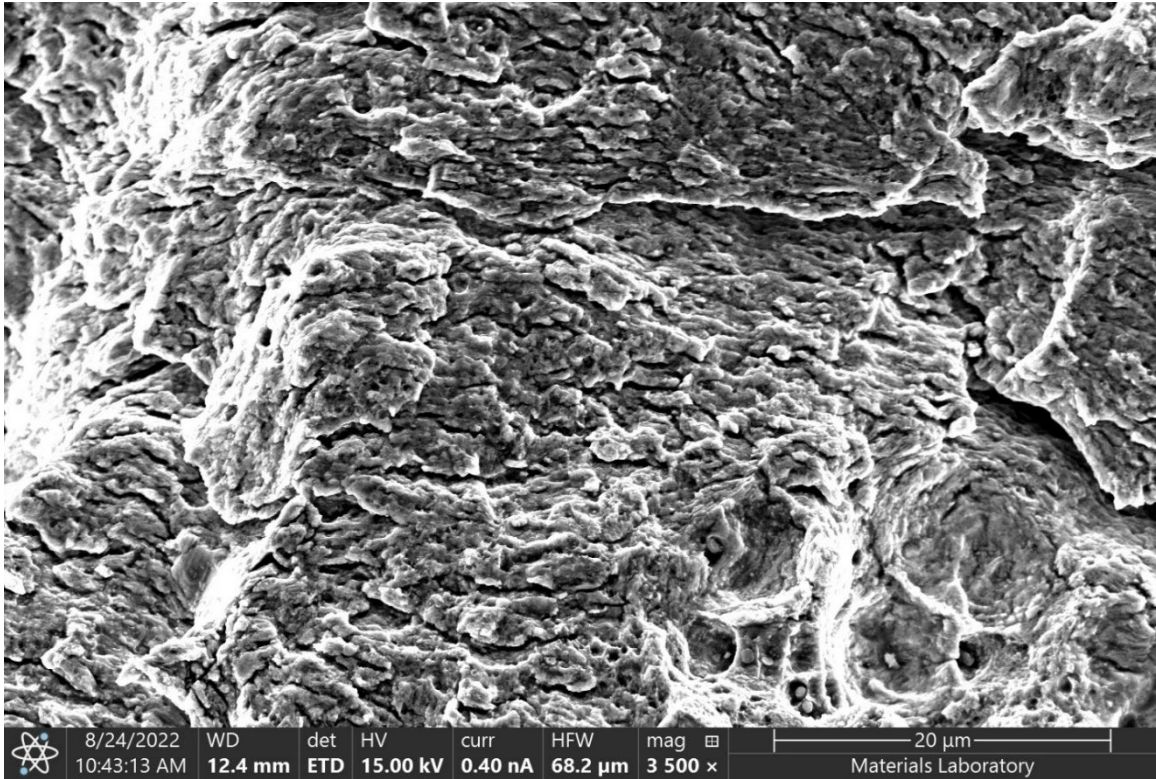


Figure 7. Secondary electron (SE) micrograph of fatigue striations on the tooth 3 fracture surface.

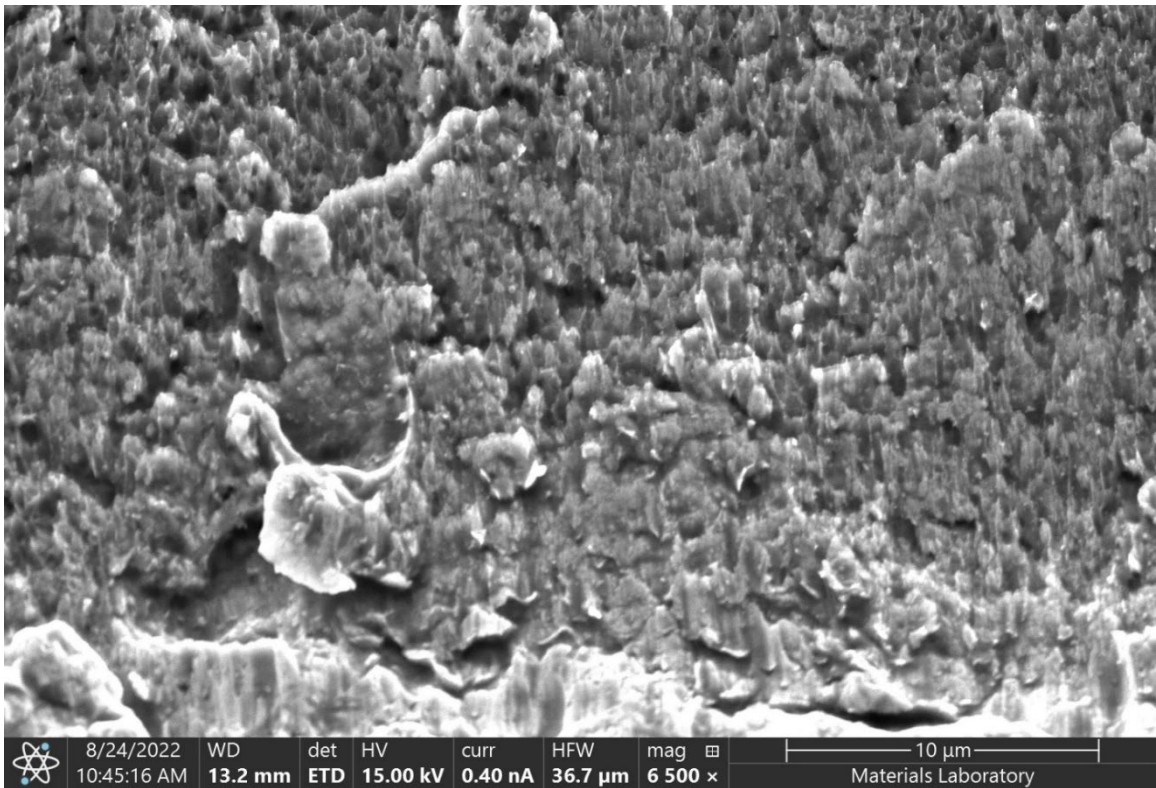


Figure 8. SE micrograph of dimpled rupture outside the fatigue crack on tooth 3.

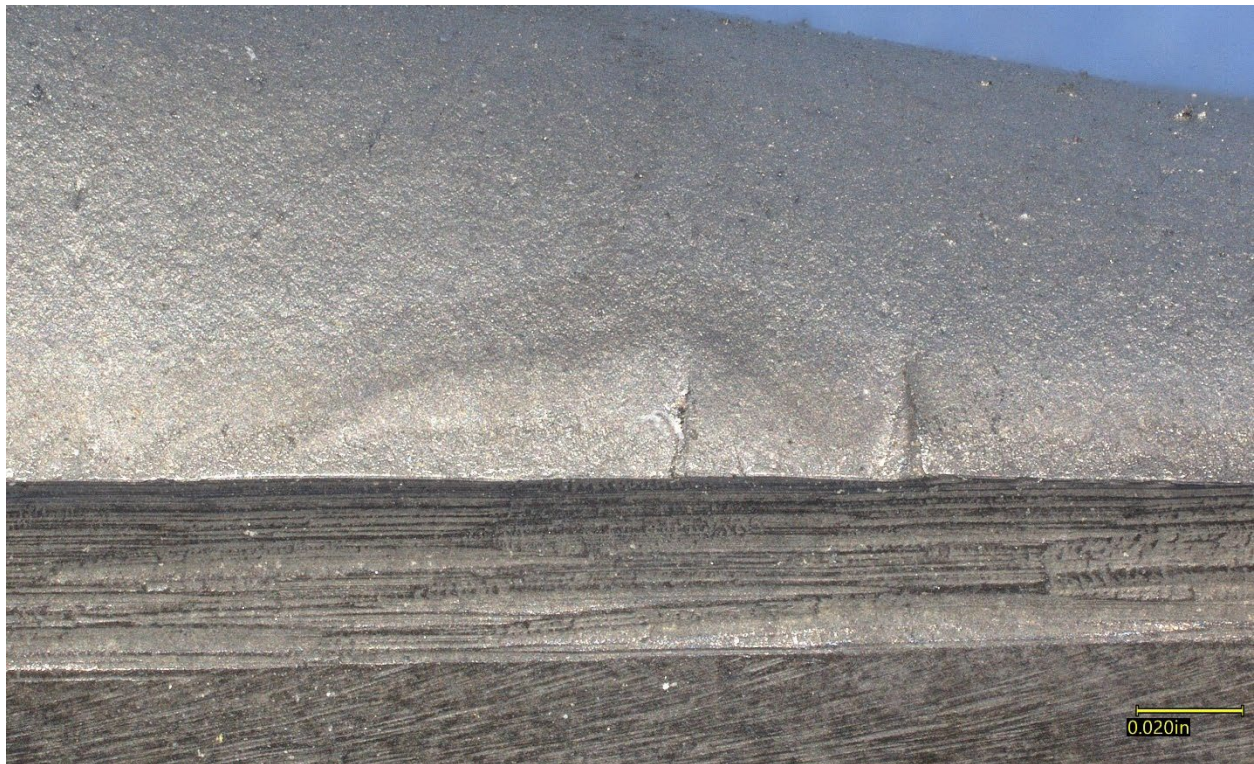


Figure 9. Closer view of the crack initiation sites and ratchet marks on the side of tooth #3.

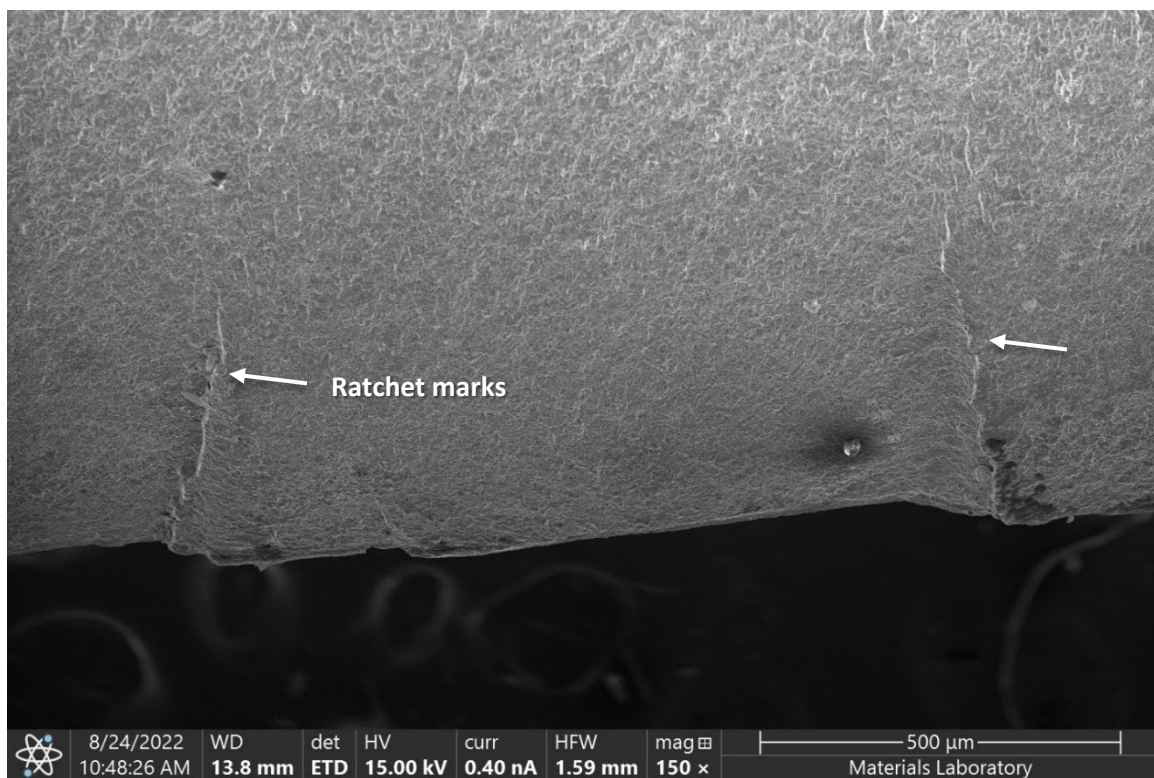


Figure 10. SE micrograph of several crack initiation sites of the fracture surface edge of tooth #3, highlighting the ratchet marks (yellow arrows).

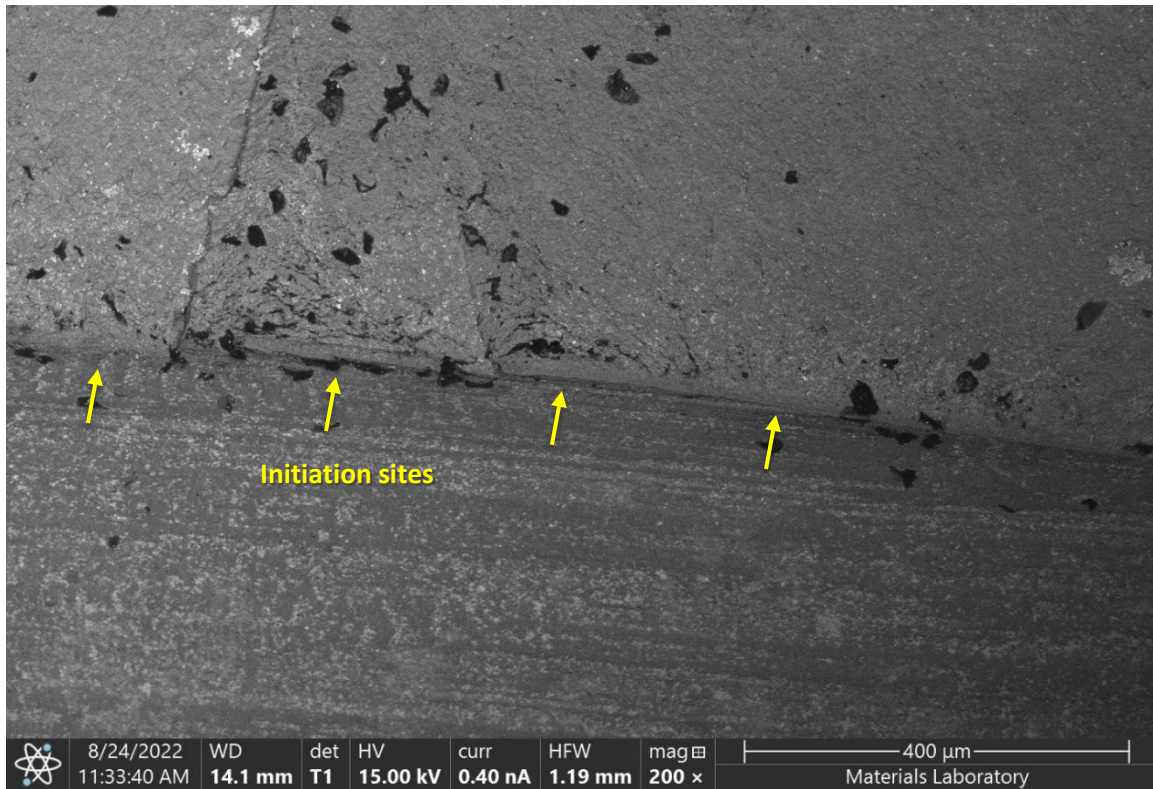


Figure 11. Backscattered electron (BE) micrograph of two of the crack initiation sites.

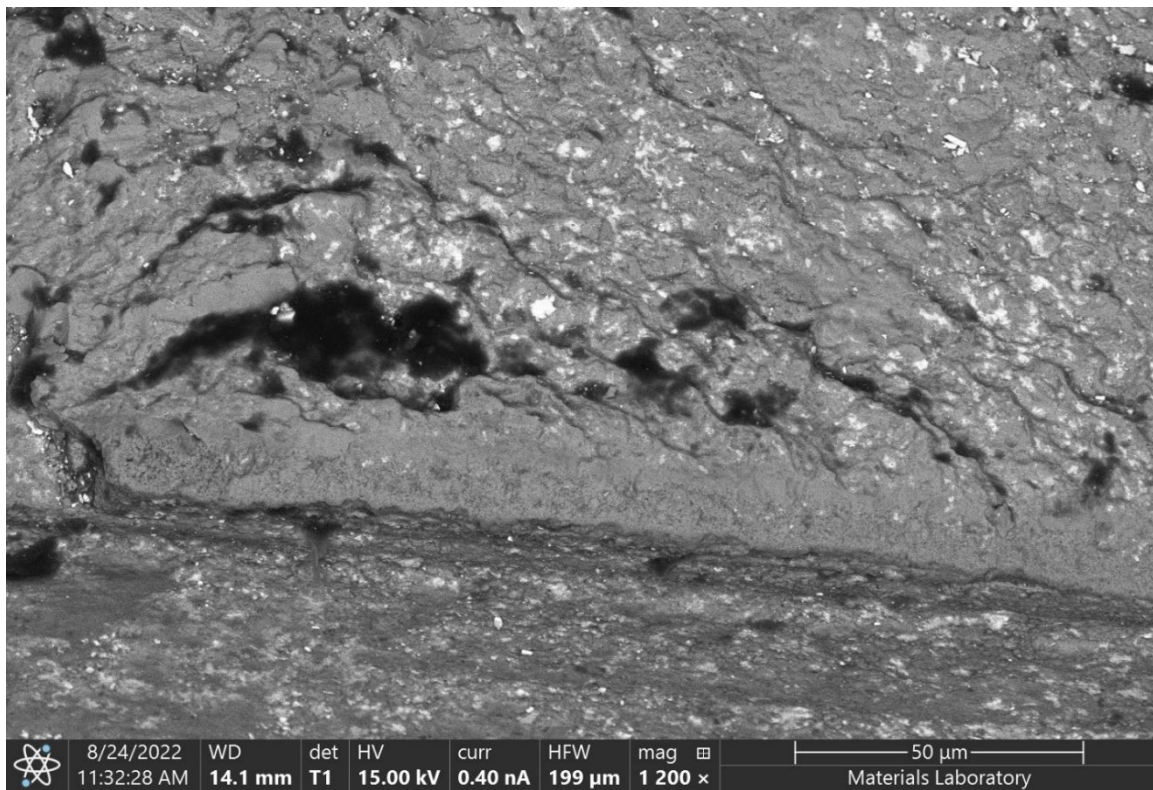


Figure 12. BE micrograph of the initiation site with the arrow in Figure 11.

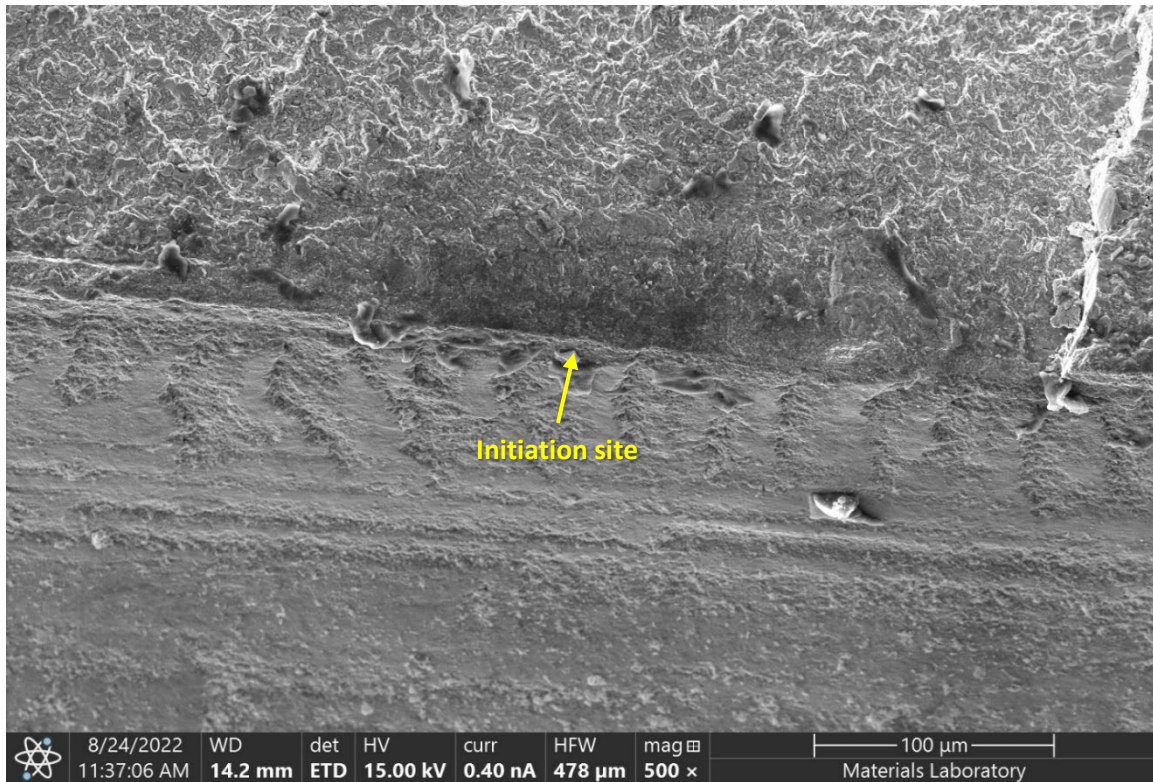


Figure 13. SE micrograph of the crack initiation site to the left in Figure 11.

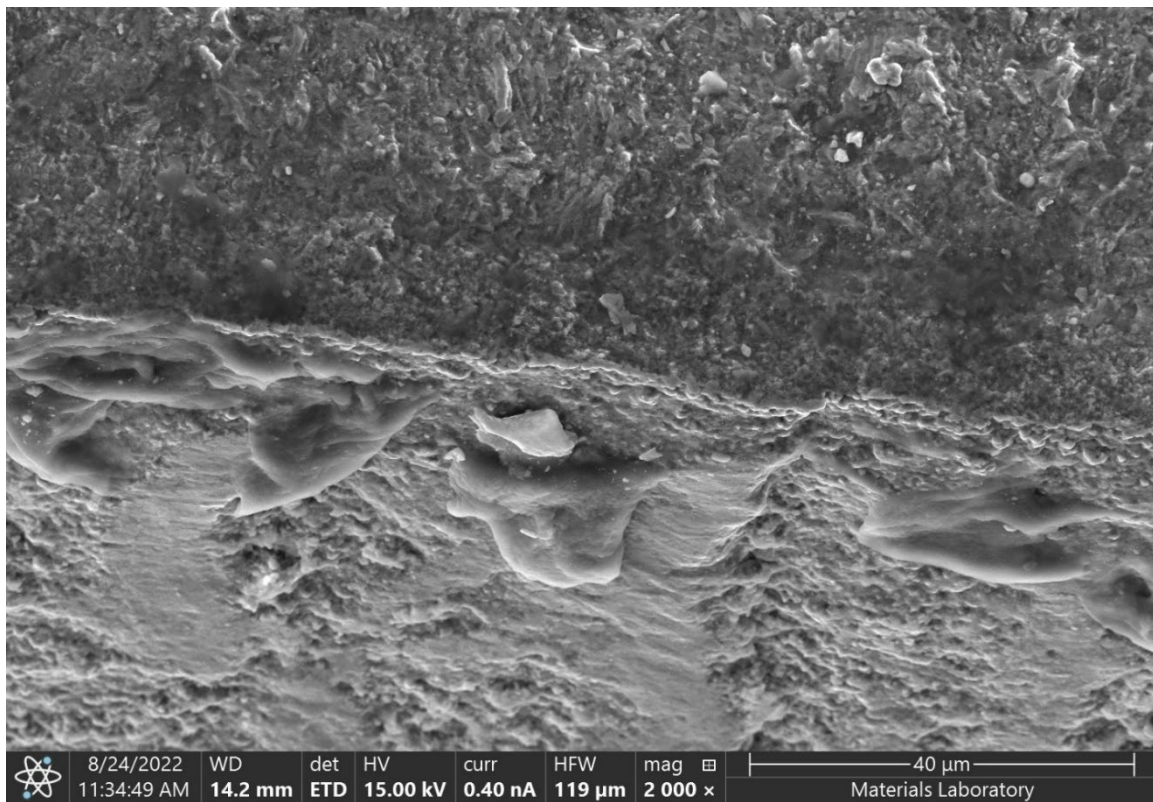


Figure 14. SE micrograph highlighting the crack initiation site in Figure 13.



Figure 15. Views of the fractured gear tooth #4, viewed from (a) the fracture surface and (b) the side.

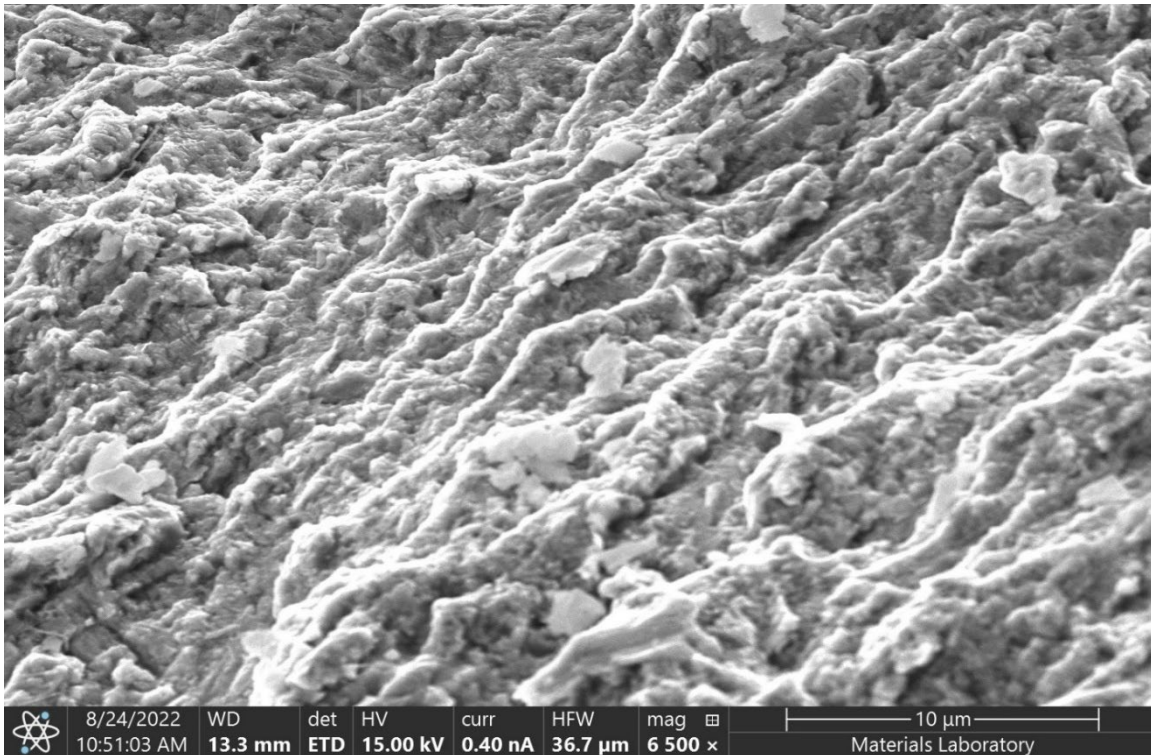


Figure 16. SE micrograph of a typical view of fatigue striations on the tooth #4 fracture surface.

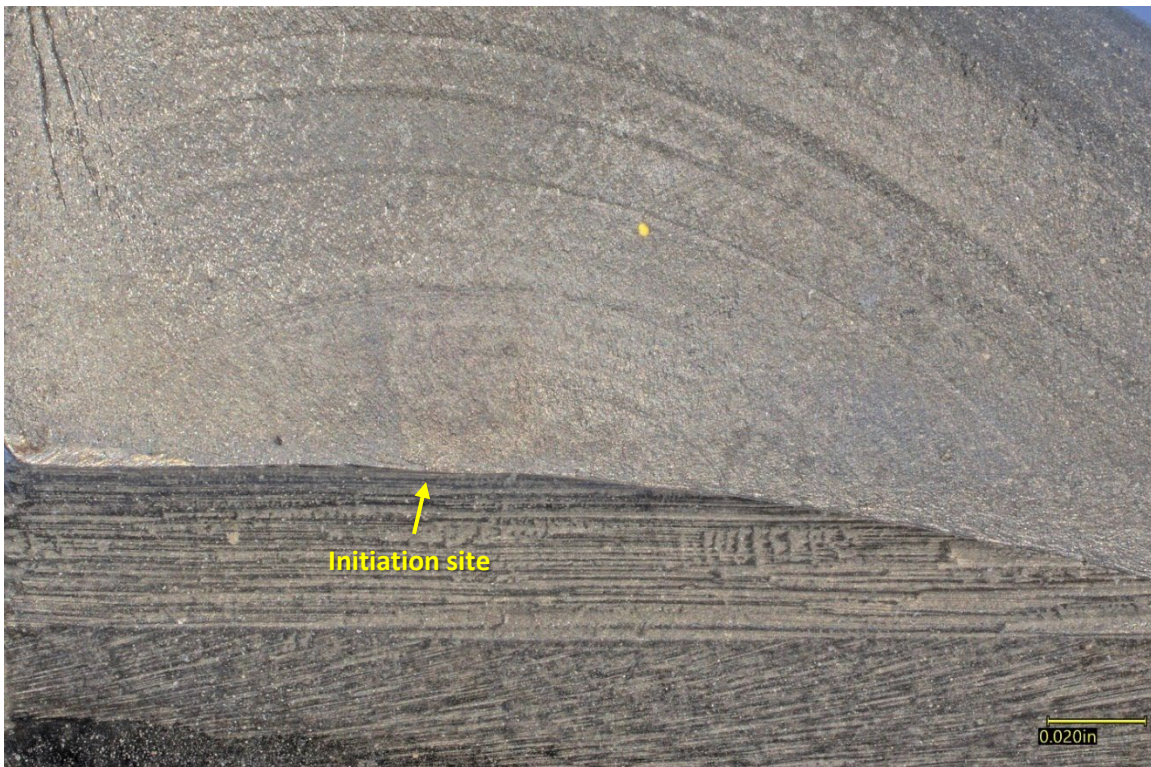


Figure 17. View of the crack initiation site and propagating crack arrest marks on tooth 4.

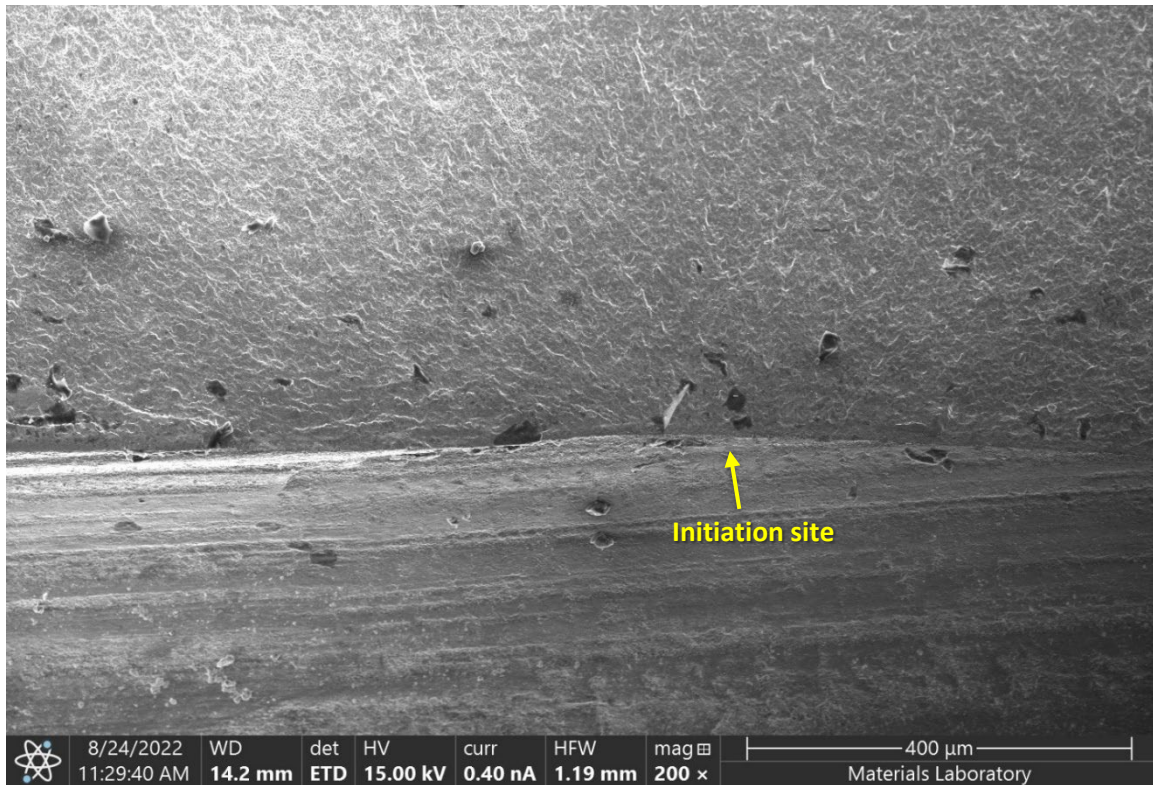


Figure 18. SE micrograph of the crack initiation site on tooth 4.



Figure 19. BE micrograph highlighting a closer view of the initiation site in Figure 18.

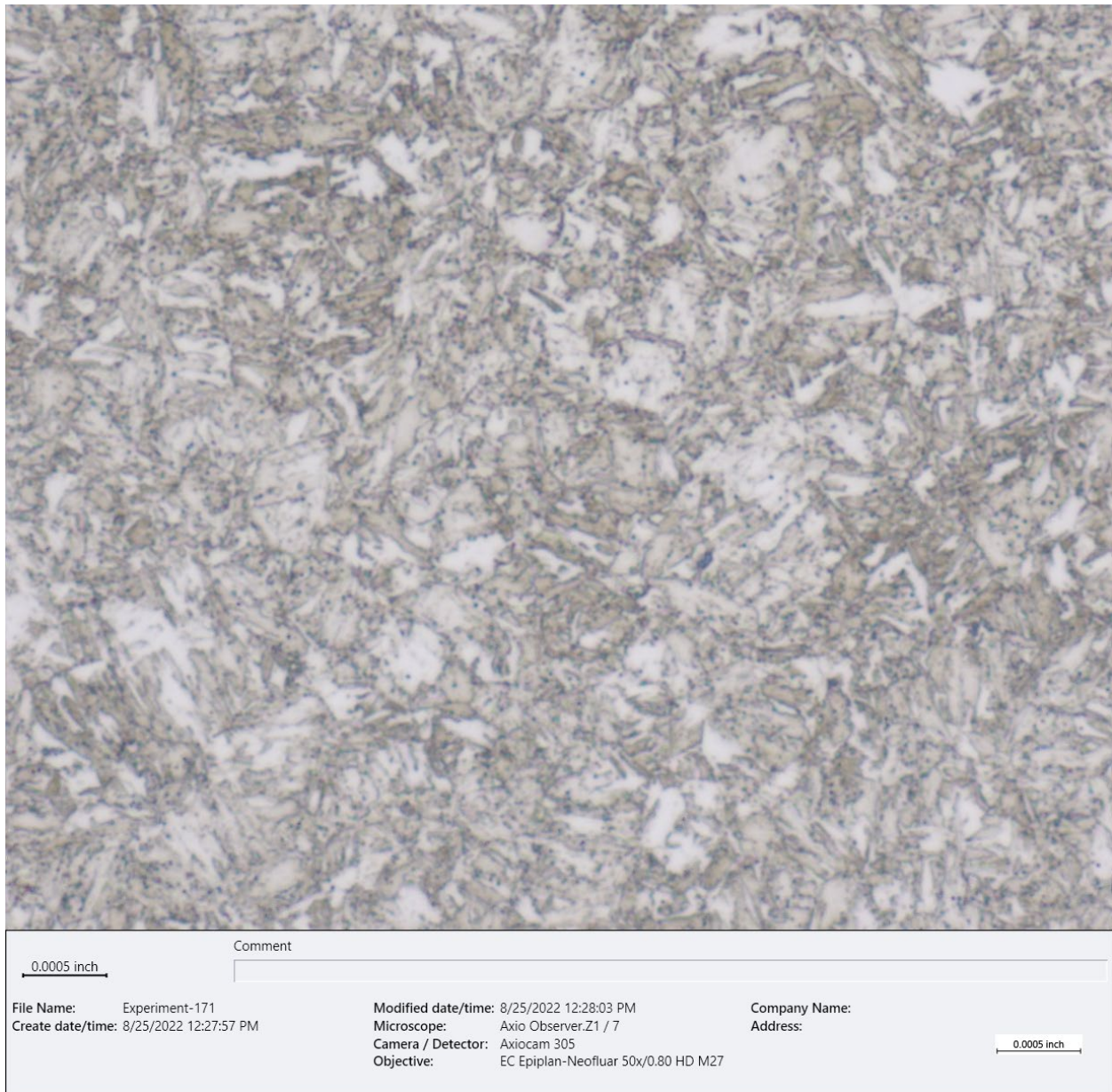


Figure 20. Bright-field (BF) optical micrograph of a typical area of the gear tooth microstructure, showing ferrite and tempered martensite constituents (~1000X, etched 2% Nital).

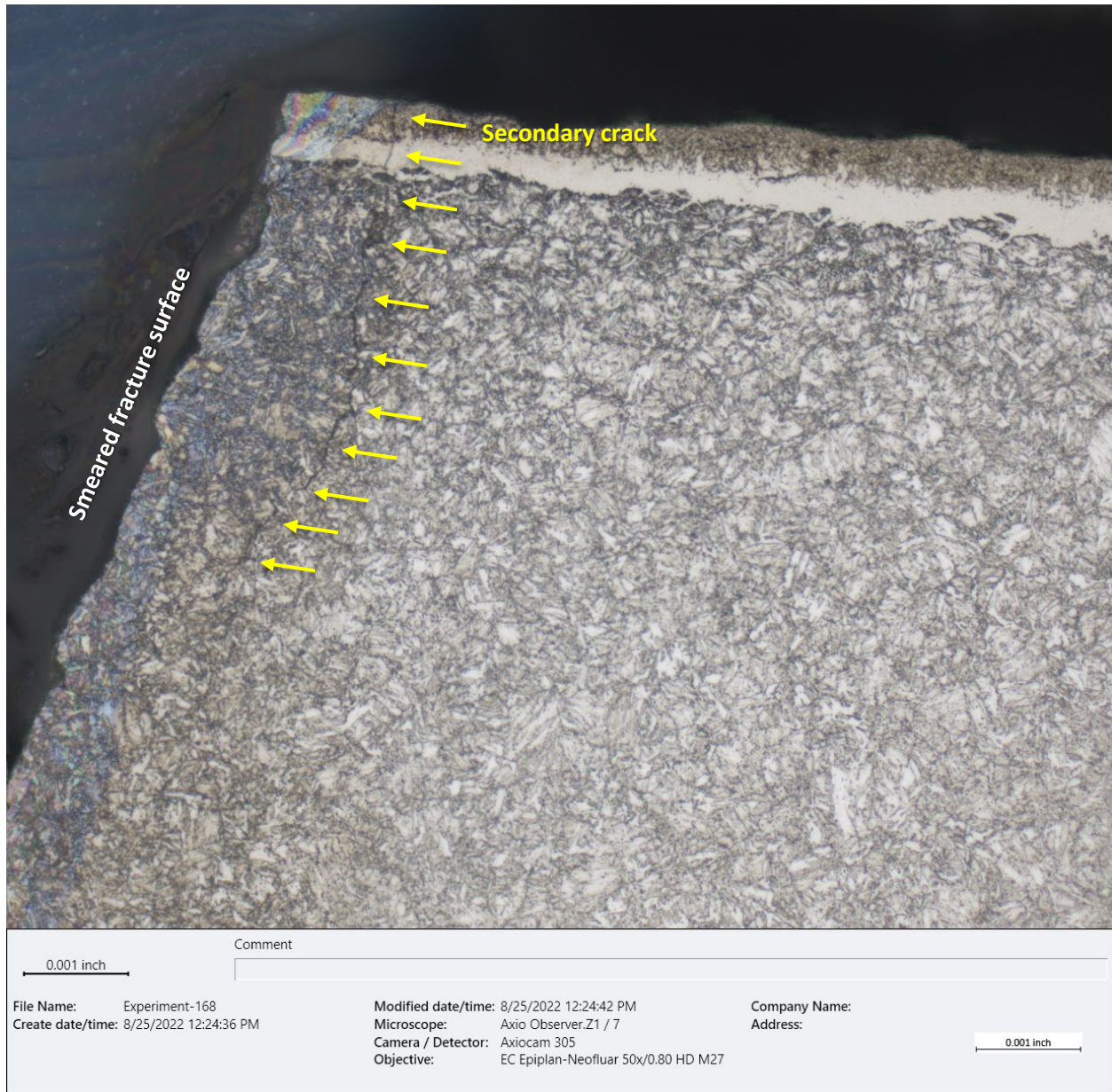


Figure 21. BF optical micrograph of an area adjacent to the tooth fatigue fracture surface, showing a parallel secondary crack (arrows) (~500X, etched 2% Nital).

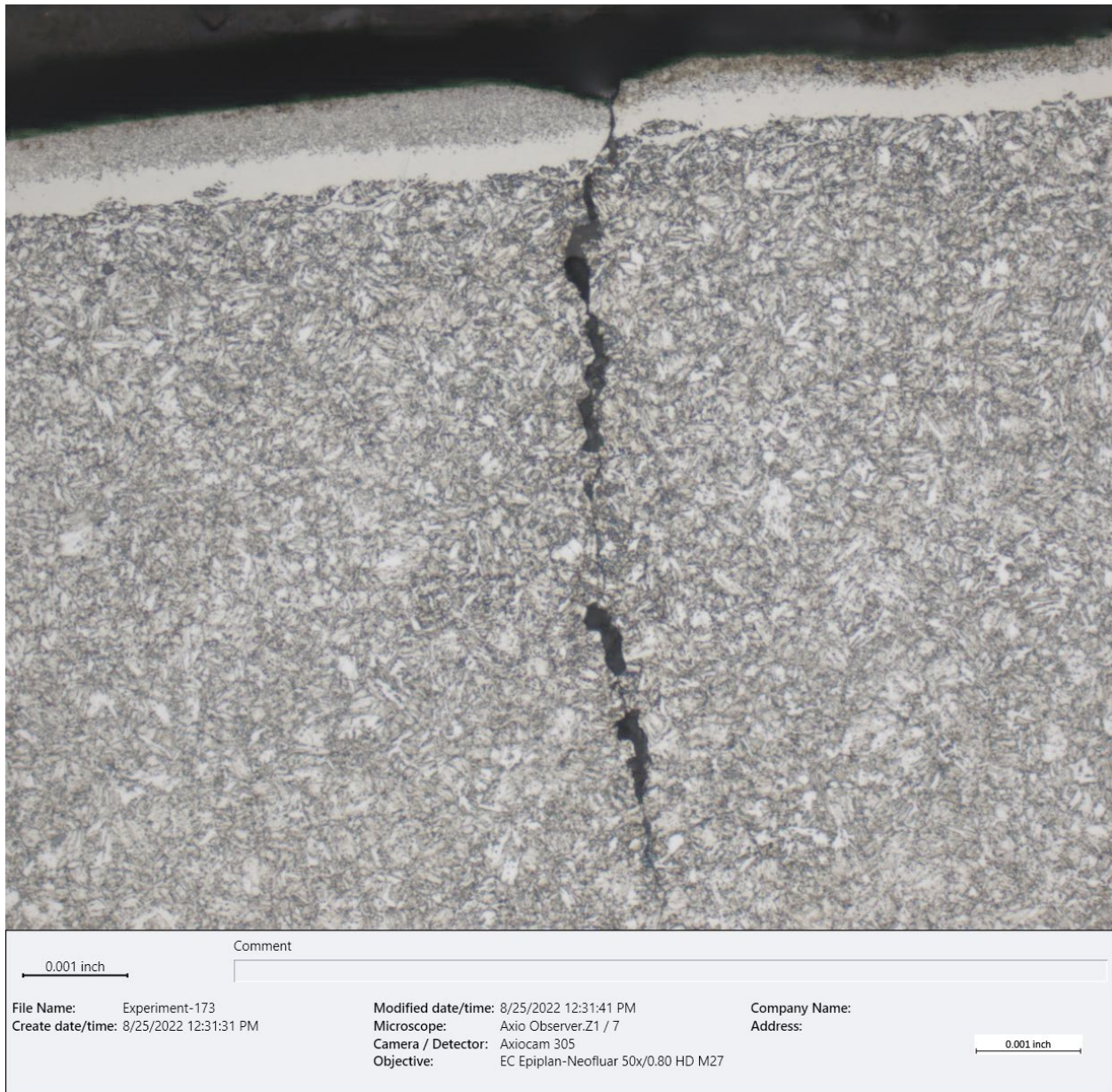


Figure 22. BF optical micrograph of a surface crack on the opposite side of the tooth shown in Figure 21, located away from the fracture surface, located through a surface nitride layer (~500X, etched 2% Nital).