National Transportation Safety Board
Office of Research and Engineering
Washington, DC 20594

CEN23LA062

# MATERIALS LABORATORY

Factual Report 24-003

**January 31, 2024**

(This page intentionally left blank)

## A. ACCIDENT INFORMATION

Location: Addison, Texas
Date: December 12, 2022
Time: 20:05 central daylight time
01:05 coordinated universal time
Vehicle: Mooney M20K, N231GZ
Investigator: Tim Sorenson, AS-CEN

## B. COMPONENTS EXAMINED

Pieces of a camshaft gear
Fragments of gear teeth
Miscellaneous metal debris

## C. EXAMINATION PARTICIPANTS

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

## D. DETAILS OF THE EXAMINATION

On December 12, 2022, a Mooney M20K was substantially damaged when it was involved in an accident near Addison, TX. The pilot and passenger were seriously injured. The pilot reported that the engine lost power and, being unsuccessful in restarting the engine, planned a forced landing along a road. During the approach, the airplane impacted a power line pole, which substantially damaged the fuselage and wings. Following an engine teardown of the Continental TSIO-520-NB17B (S/N 822302-R) reciprocating engine, the camshaft gear and loose fragments consistent with having fractured from the gear were recovered and sent to the NTSB Materials Laboratory for additional examination.[1] The assembly date for this engine was July 01, 2001.

Figure 1 shows the gear from the aft face, as received with six liberated teeth packaged in clear tape. As illustrated in Figure 2, many of the gear teeth were intact, but 11 were either damaged or separated from the gear (Figure 2b). Figure 3 shows the area of the fractured and damaged gear teeth from the side. These were labeled 1 through 9 for the purposes of this report, increasing clockwise as shown in the figure (10 and 11 were not assigned as those teeth were plastically deformed rather than fractured). As shown on the face in Figure 3, the markings on the gear stated "655516 A" and "PG 06/01".

[1] The TSIO-520 is a family of turbo-charged, fuel-injected, air-cooled, horizontally opposed, six-cylinder aircraft engines manufactured by Continental Motors, headquartered in Mobile, AL.

Figure 4 shows several fracture surfaces and areas of plastic deformation on teeth positions 1 through 8. Several fracture surfaces exhibited crack arrest marks, indicating crack propagation under cyclic loading. In addition, an examination of the land and flank facing the fracture surface of tooth 1 did not exhibit an indication of excessive wear or gouging.

The fracture surface of the missing teeth 1 through 9 on the camshaft gear are shown in Figures 5 through 13, respectively. Teeth 5 and 6 exhibited indications of smeared material and missing face material above the pitch circle of the threads. There were also features consistent with batter, sliding, and gouging, consistent with the plastic deformation of these threads. The direction of plastic deformation was upward in Figures 9 and 10. These threads were consistent with being present and then damaged after the adjacent threads fractured.

All of the other fractured threads exhibited some degree of crack arrest marks, consistent with progressive cracking. However, threads 1 and 2 revealed the most significant degree of surface demonstrating said features and were the focus of the examination. Figures 5 and 6 show the fracture surfaces of tooth positions 1 and 2, respectively. Both exhibited concentric crack arrest marks, consistent with initiating along the lower fracture edges in both figures, consistent with the locations of the fillet radii from each tooth. The initiation areas exhibited upward-facing ratchet marks.

Figure 14 shows the mating fracture surface of the liberated tooth 1. The features, such as the crack arrest and ratchet marks, mirror that of the gear fracture shown in Figure 5. The crack exhibited ratchet marks near the edge, indicating multiple crack initiation sites. This area was coincident with the area from which the crack arrest marks emanated, illustrated in Figure 15. Figure 16 shows a closer view of the initiation area, demonstrating the ratchet marks. The area along the flank and fillet radius did not exhibit any plastic deformation or wear significant enough to show gouge marks. There were also no indications of corrosion at that location.

The fractured tooth 1 was examined using a field emission scanning electron microscope (SEM). Figures 17 and 18 show a typical area in the center of the fracture surface. As shown in a closer view in Figure 19, the fracture surface exhibited fatigue striations, consistent with fatigue crack propagation. These features were found throughout the tooth fracture surface, except for a thin region near the top of the area shown in Figure 14. Also at the top of the tooth fracture surface in Figure 14, there were fatigue striations, consistent with propagating inward from the opposite fillet radius.

The initiation region in Figure 16 is shown in Figure 20 as seen using a SEM. The ratchet marks demark the separate crack initiation sites where the cracks coalesced during propagation. Figure 21 shows a backscattered micrograph illustrating areas of surface contamination (dark colored) near the initiation region edge.[2] A closer view of the leading crack initiation site is shown in Figure 22. This area was absent of material or mechanical defects but exhibited faint striations emanating from the edge. Another initiation site shown in Figure 23 revealed similar features.

The fractured #2 tooth was mounted and polished in cross-section for metallographic examination. Figure 24 shows a montage of the tooth in its polished condition. The fatigue fracture surface comprises the bottom surface facing downward in the image. The tooth's interior exhibited branched cracking, as shown closer to the top land. The geometry of the tooth along the fracture surface shows an upward curve consistent with the fillet radii of the gear. A closer examination of the corners near the fillet radius did not exhibit corrosion pits, nonmetallic inclusions, or mechanical defects.

The etched view of the tooth revealed the microstructure of the tooth, which exhibited a differing structure along the surface, consistent with a case hardening. Figure 25 shows a typical area of the microstructure in the core, which was consistent with tempered martensite. Figure 26 shows the surface, which exhibited a white surface layer and a darker subsurface.

The tooth cross-section was examined using energy-dispersive X-ray spectroscopy (EDS). The composition of the gear was consistent with alloy steel. The hardness was examined using a microindentation hardness technique per ASTM E384.[3] Sampled from the surface to the core interior, the hardness decreased as the depth of hardness sampling increased. Figure 27 shows a chart of the hardness data in HRC converted from $HV_{500}$.[4] The surface hardness exceeded 50 HRC to a depth of about 0.01 inches. The core hardness averaged 31 HRC. These data were typical of a quench and tempered alloy steel with a surface hardening treatment.

The gear fractured from fatigue cracking that initiated on multiple teeth along one side. The fatigue cracks had initiated along the fillet radii and propagated inward. While the main fatigue crack front bore through the tooth cross-section, additional cracks initiated on the opposite fillet radii and propagated inward. When the cracks were deep enough, the remaining tooth cross sections fractured from overstress. After the first tooth separated, the remainder of the teeth with deep fatigue cracks

---

[2] Backscattered electrons: SEM micrographs produced using backscattered electrons display contrast that is associated with the atomic numbers of the elements in the micrograph. Materials containing elements with higher atomic numbers visually appear lighter relative to other materials containing elements with lower atomic numbers.

[3] ASTM E384 – *Standard Test Method for Knoop and Vickers Hardness of Materials*. ASTM International, West Conshohocken, PA.

[4] HRC or Rockwell C scale is an indentation method for determining the hardness of harder metal alloys using a conical diamond indenter and 150 kg major load. $HV_{500}$ is an indentation hardness measurement unit performed by applying a 500-gram load to a diamond indenter and measuring the size of the resulting impression. Higher numbers indicate harder materials.

experienced stresses high enough to fracture them, and the intact teeth were deformed plastically. These events led to the failure of the camshaft gear.

Submitted by:

Erik M. Mueller
Materials Research Engineer


**Figure 1.** View of the camshaft gear from the aft side, and six of the recovered fractured teeth (received in tape on right).

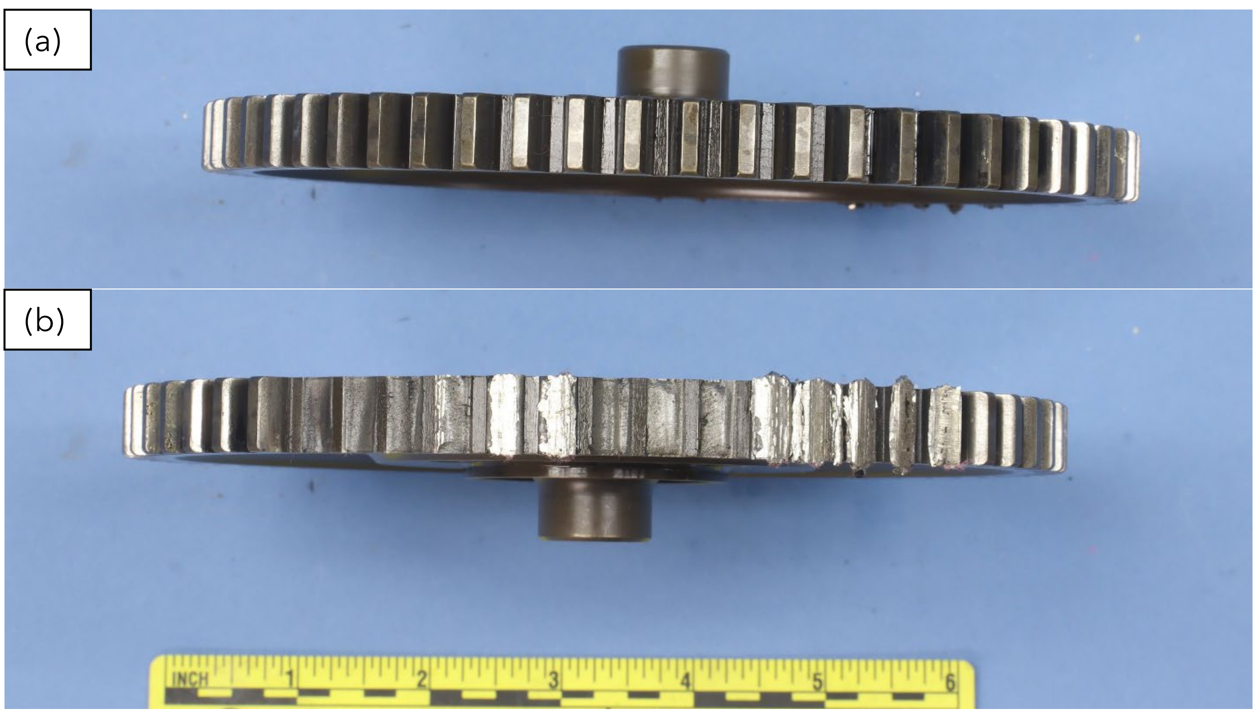


**Figure 2.** Opposing views of the teeth from the camshaft gear, showing (a) an intact side and (b) the side with multiple missing, deformed, and flattened teeth.

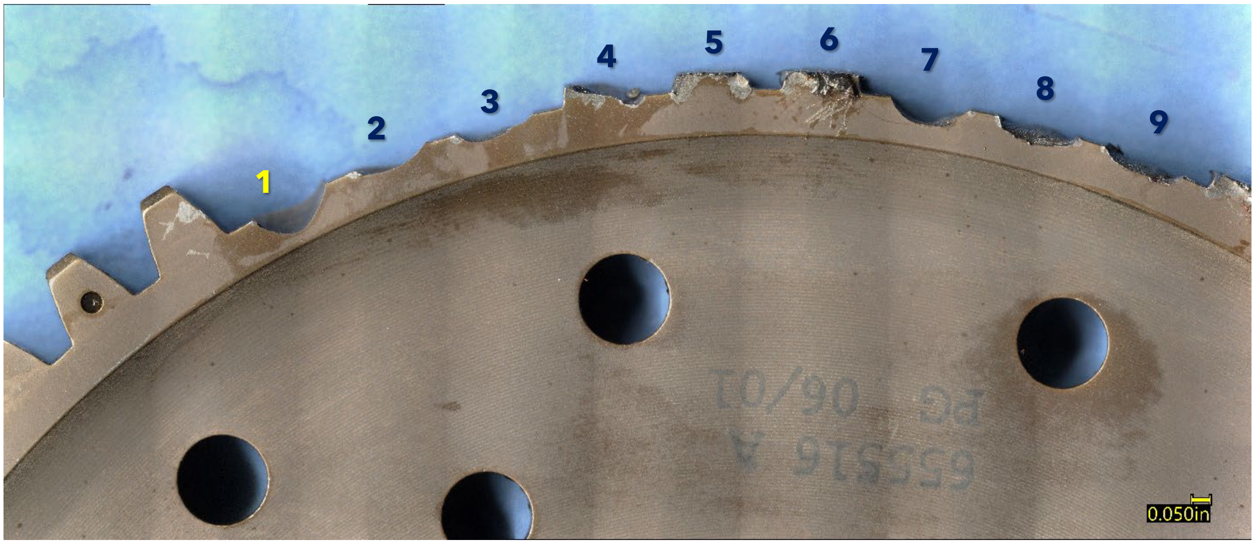


**Figure 3.** Side view montage of the fractured gear teeth, labeled 1 through 9 as annotated in the figure from left to right.

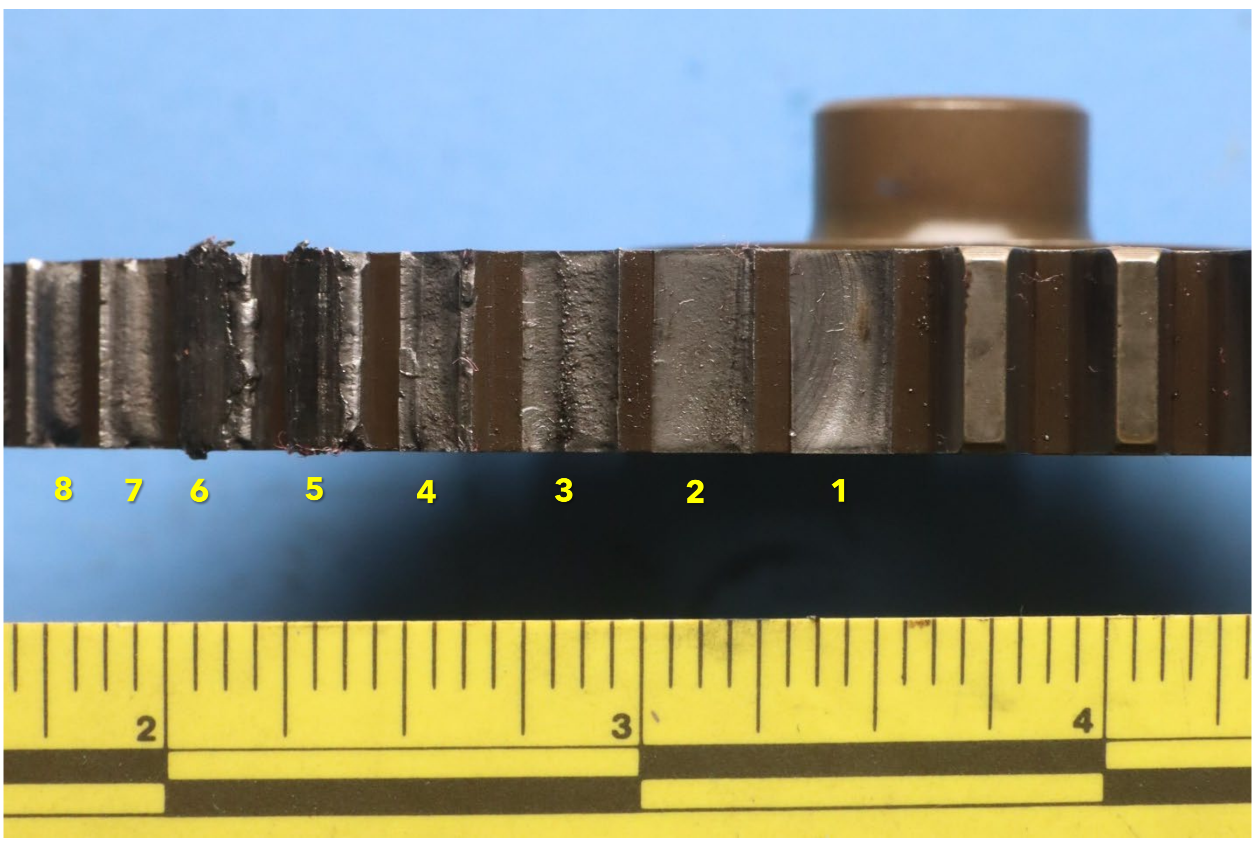


**Figure 4.** Closer view of the fractured teeth on the gear, labeled from right to left in the figure.


**Figure 5.** View of the fracture surface of tooth 1, showing crack arrest marks from the bottom left.


**Figure 6.** View of the fracture surface of tooth 2, showing crack arrest marks from the bottom and top.


**Figure 7.** View of the fracture surface of tooth 3.


**Figure 8.** View of the fracture surface of tooth 4.


**Figure 9.** View of the fracture surface of tooth 5.


**Figure 10.** View of the fracture surface of tooth 6.

**Figure 11.** View of the fracture surface of tooth 7.

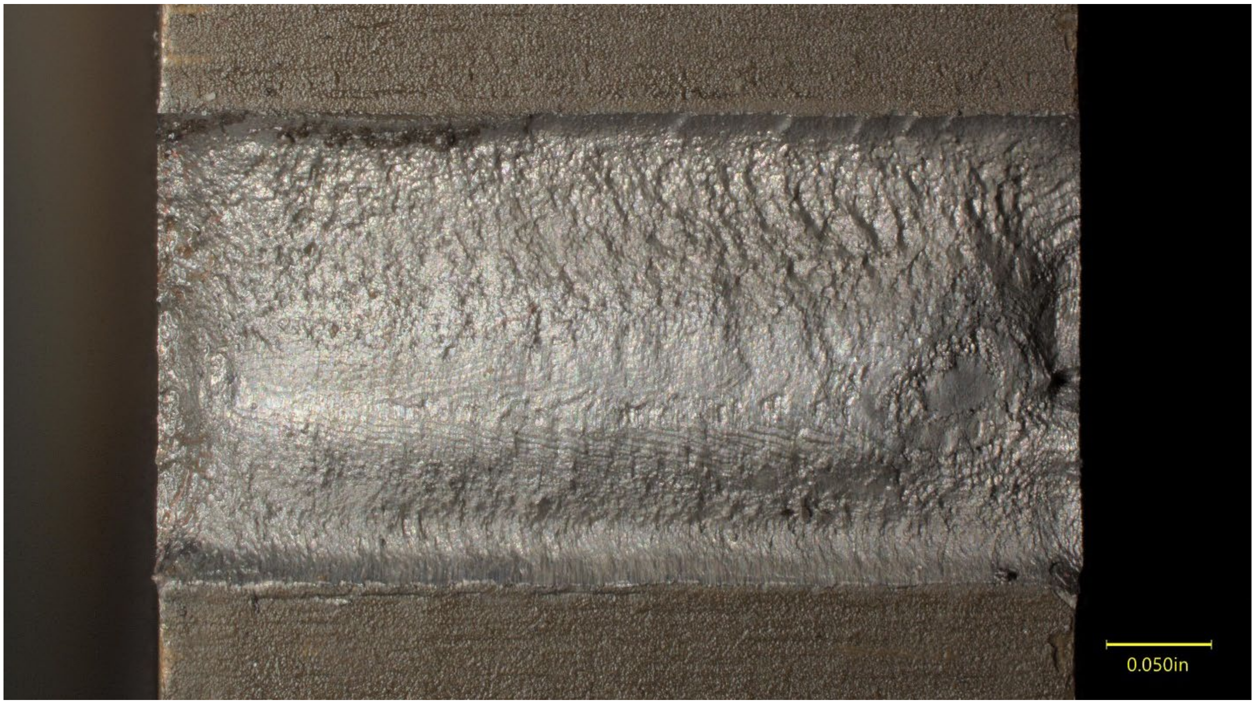

**Figure 12.** View of the fracture surface of tooth 8.


**Figure 13.** View of the fracture surface of tooth 9.


**Figure 14.** View of the fracture surface of tooth 1, which mated to the surface in **Figure 5**.


**Figure 15.** Angled view of tooth 1 in **Figure 14**, showing the edge of the fracture.


**Figure 16.** Closer view of the edge of the tooth fracture, showing ratchet marks and crack arrest marks emanating from the crack initiation location.

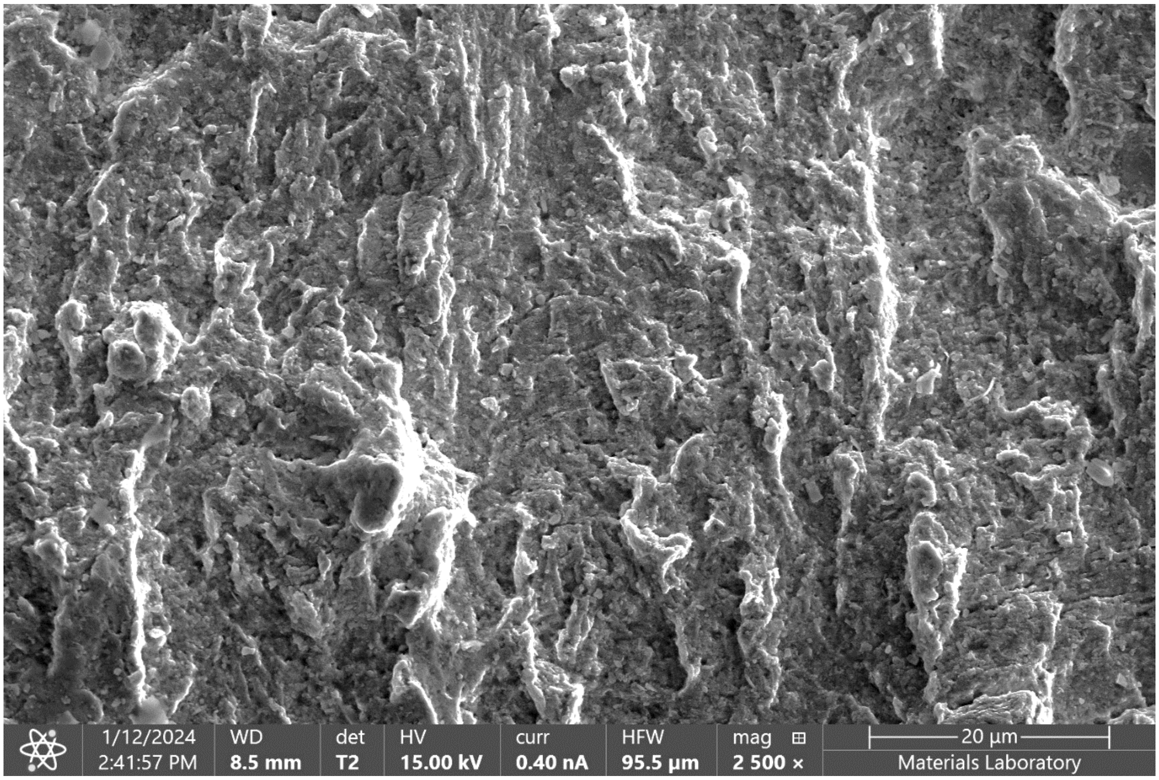

**Figure 17.** Secondary electron (SE) micrograph of a typical area of the fracture surface of tooth 1, showing fatigue striations.

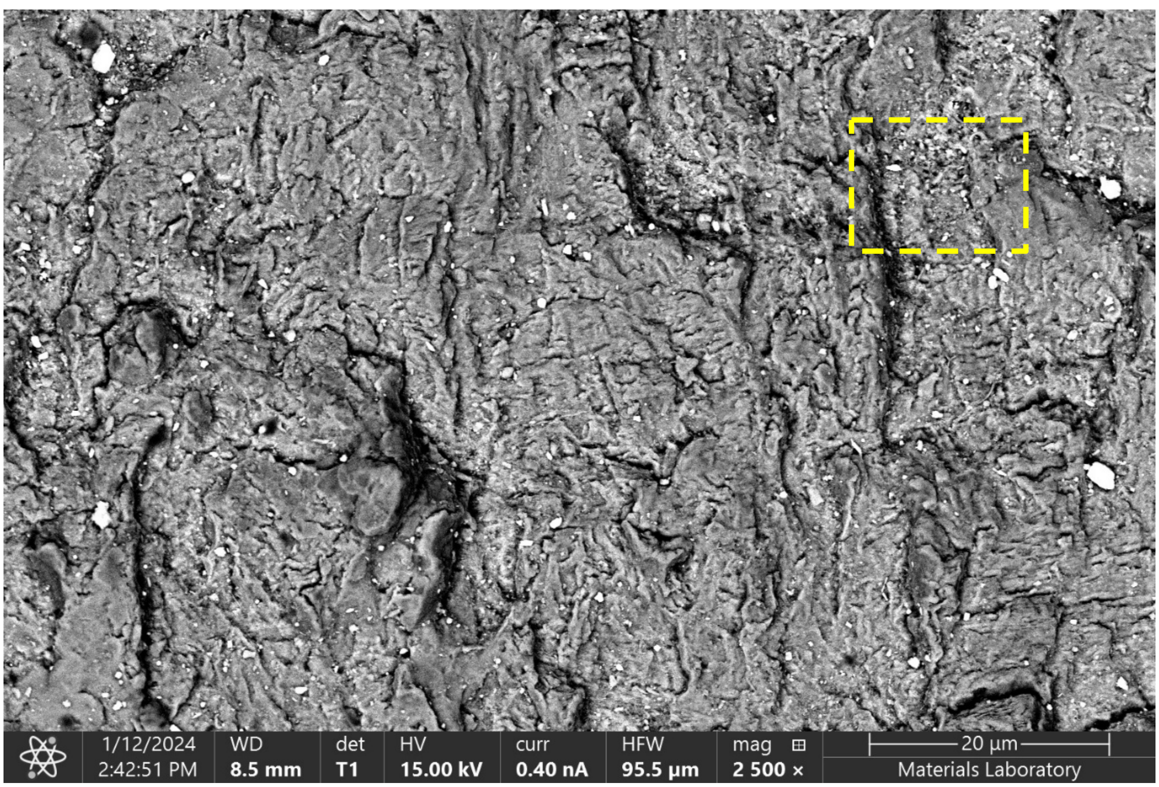

**Figure 18.** Backscattered electron (BE) micrograph of the area shown in **Figure 17**.

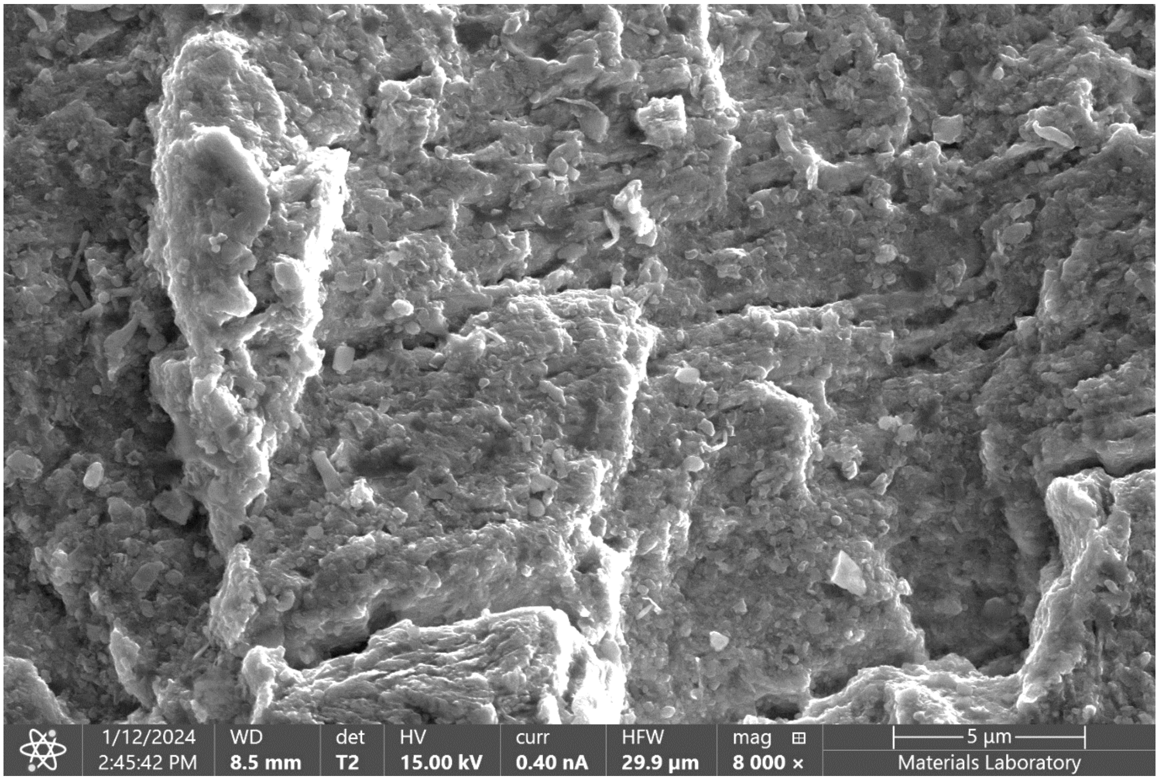

**Figure 19.** SE micrograph of the boxed area in **Figure 18**, showing fatigue striations.

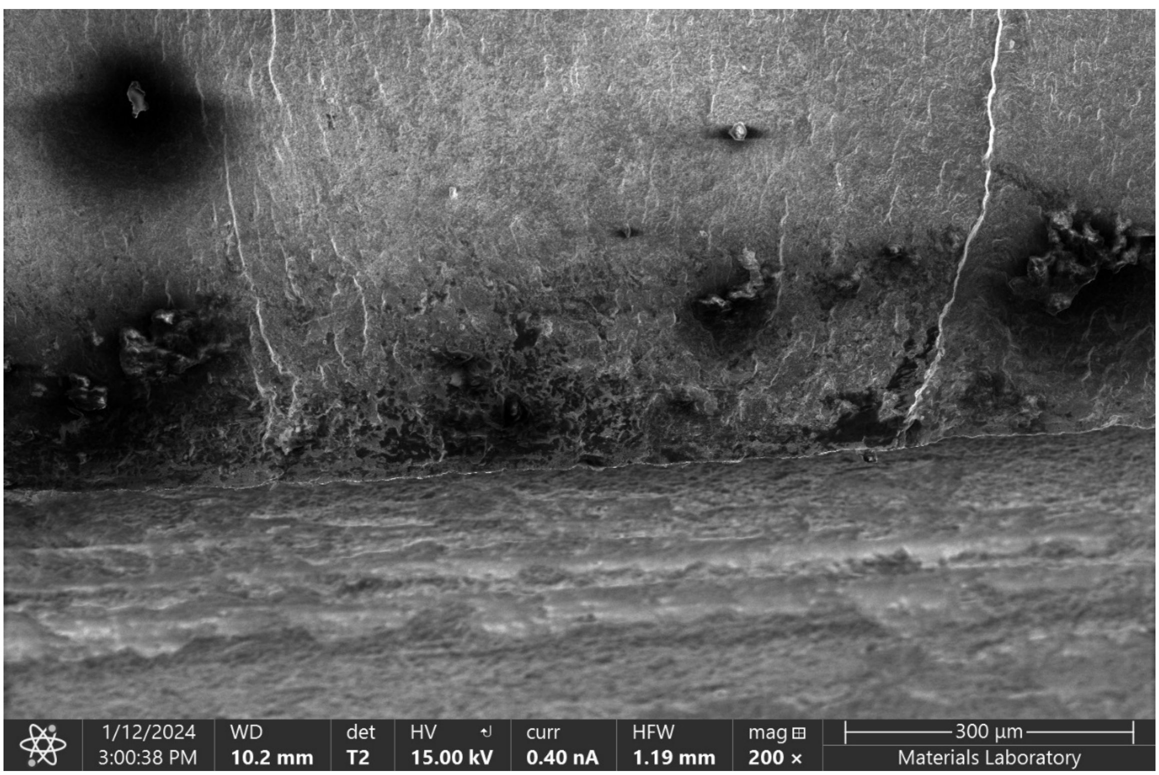

**Figure 20.** SE micrograph of a the crack initiation area of tooth one, along the edge shown in **Figure 16**.

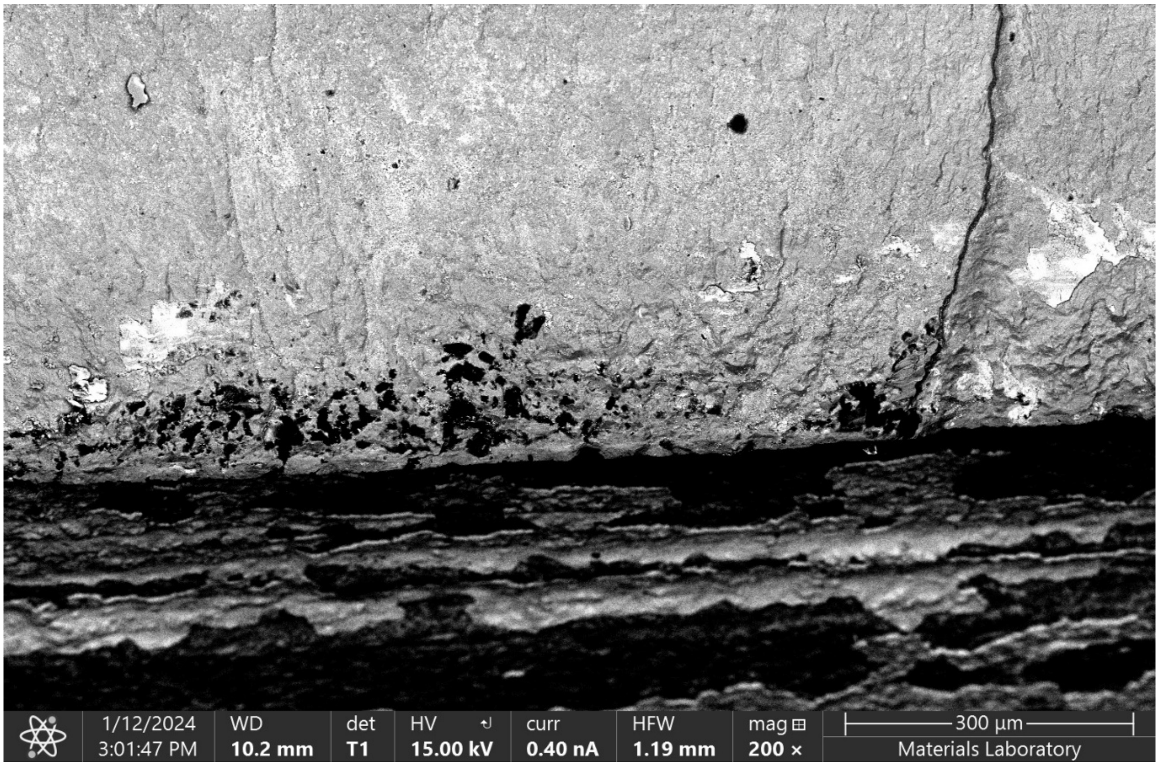


**Figure 21.** BE micrograph of the initiation region in **Figure 20**.

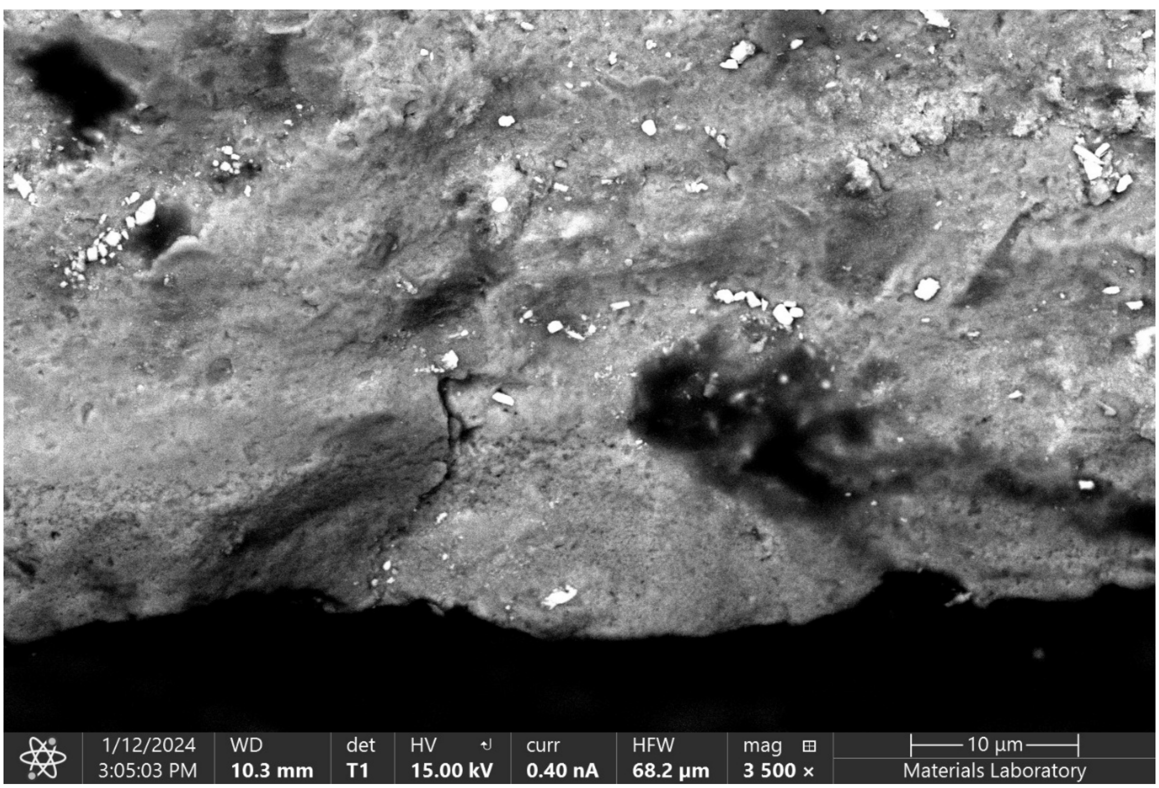


**Figure 22.** BE micrograph of one of the crack initiation sites in **Figure 21**.

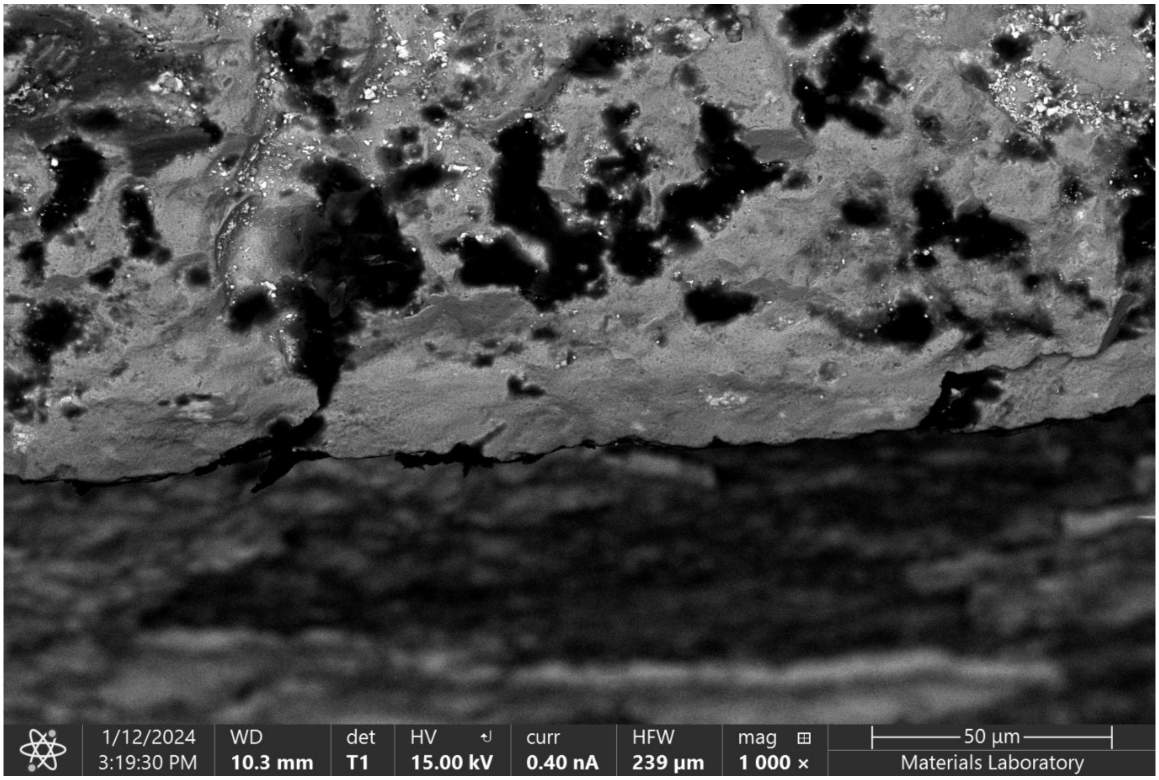

**Figure 23.** BE micrograph of another crack initiation site in **Figure 21**.

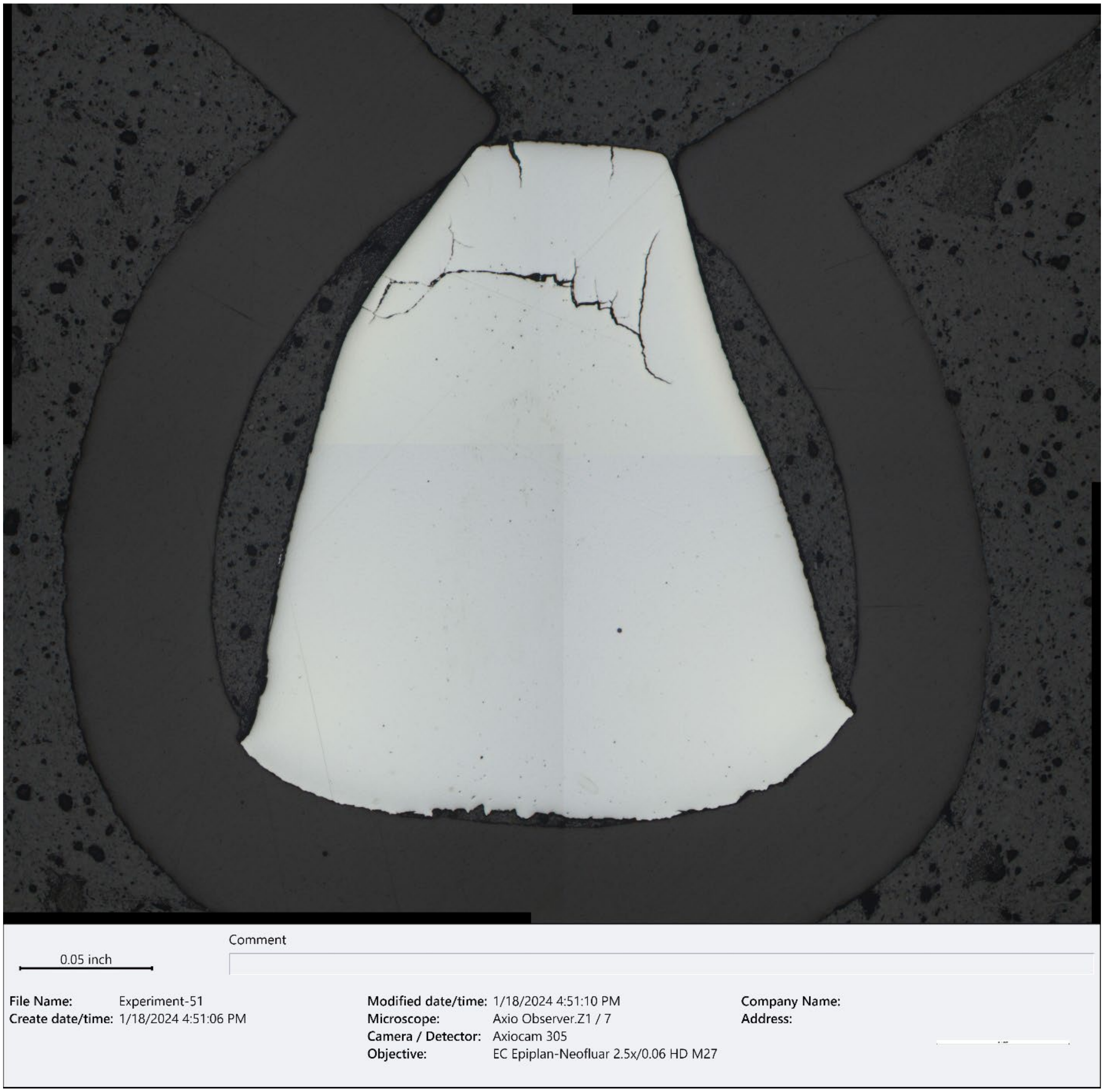


**Figure 24.** Optical bright field (BF) micrograph of a cross-section of the second fractured tooth, with the fracture surface on the bottom (~25X, as-polished, montage).


**Figure 25.** BF optical micrograph of a typical area of the core of the fractured tooth in Figure 24 (~500X, etched 2% Nital).

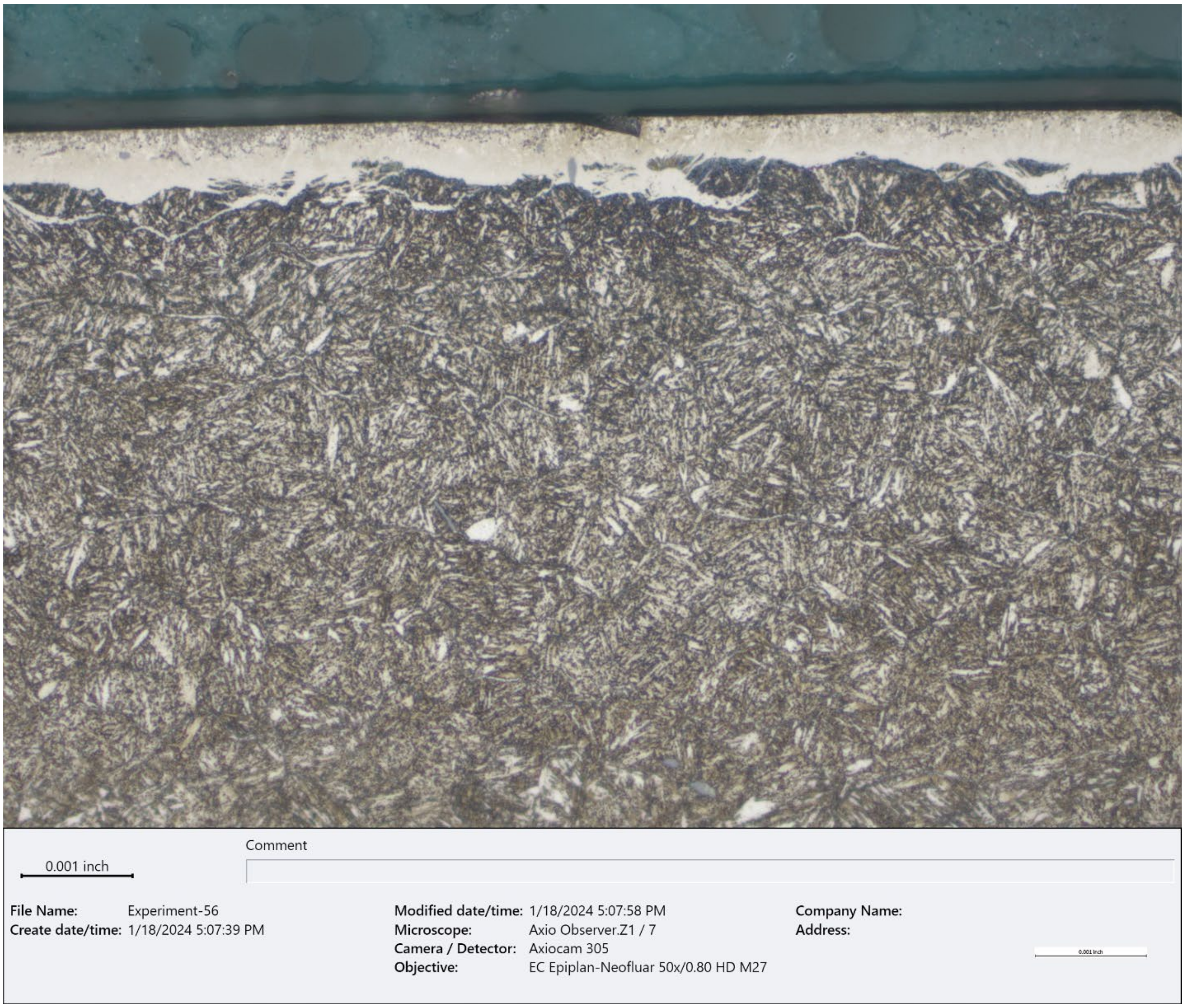


**Figure 26.** BF optical micrograph of a typical area of the tooth surface (flank), showing a contrasting surface layer (~500X, etched 2% Nital).

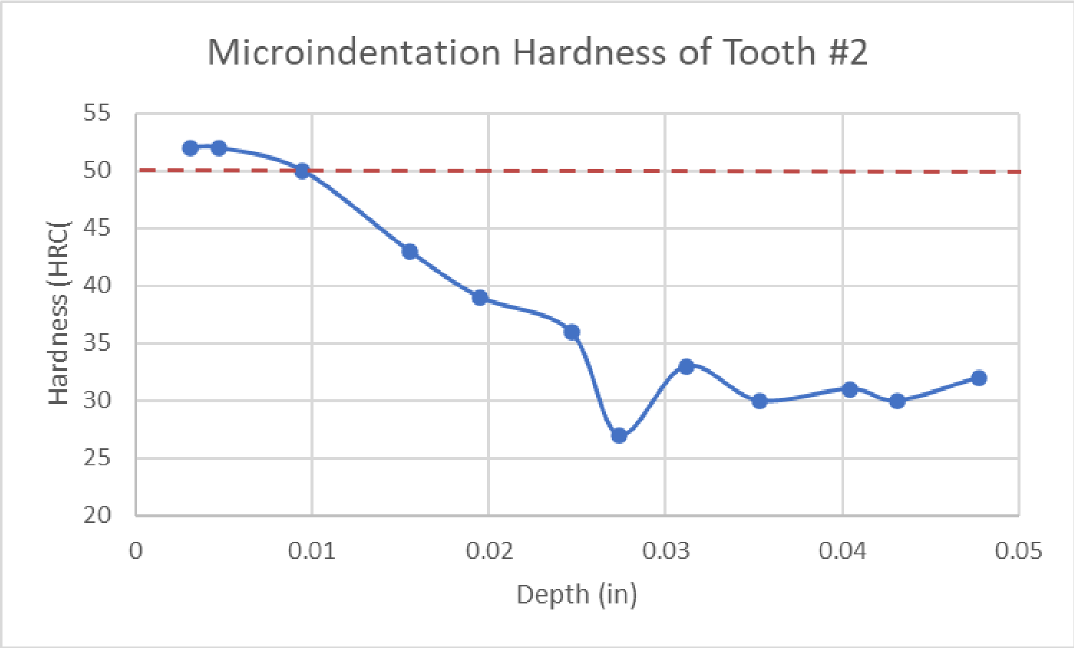


**Figure 27.** Chart of the microindentation hardness of tooth #2 from a flank surface inward, plotted against depth (in inches). The orange dashed line represents the minimum case depth hardness of 50 HRC.