

NATIONAL TRANSPORTATION SAFETY BOARD

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



September 29, 2014

MATERIALS LABORATORY TESTING REPORT

Report No. 13-087

1. INCIDENT INFORMATION

Place : Charleston, South Carolina
Date : July 28, 2012
Vehicle : Boeing 787-8, ZA238
NTSB No. : DCA12IA114
Investigator : Dave Helson, AS-10

2. COMPONENTS EXAMINED

- GEnx engine fan midshaft (ESN 956-121 and ESN 956-175)
- Fan midshaft retaining nut (ESN 956-121 and ESN 956-175)

3. DETAILS OF THE EXAMINATION

3.1. Background and Timeline of Events

On July 28, 2012, a Boeing 787-8 airplane experienced a loss of thrust in the right engine during a pre-flight, low speed taxi test at Charleston International Airport in Charleston, South Carolina. The test was aborted when the engine reached 78% N1 when commanded to 95.4% N1¹. The engine was a General Electric (GE) GEnx-1B turbofan engine, engine serial number (ESN) 956-121. Borescope inspection of the engine revealed the low-pressure turbine (LPT) rotor had shifted aft causing extensive damage to the LPT section of the engine. Further examination of the engine revealed the forward end of the fan midshaft (FMS) had separated from the aft portion of the shaft at the aft most external thread.

The fractured forward end of the FMS assembly with the forward lock nut and center vent tube still in place was removed from the engine and sent to GE Aviation in Evendale near Cincinnati, Ohio, for dimensional inspection and metallurgical examination. The engine was subsequently removed from the airplane and sent to GE Aviation in Cincinnati for disassembly and examination. The examination of the shaft remnant and the removed engine was performed under the guidance of the NTSB, with participating party members present. The engine had not yet been operated in flight, having only been operated during post-assembly tests at GE and post-installation ground runs at Boeing in Charleston. The fan midshaft had undergone 634 days of total

¹ N1 refers to the rotating speed of the innermost rotating shaft with the fan/booster and low-pressure turbine sections of the engine, here given as a percentage of maximum RPM.

time clamped to the adjacent components and 18 hours (2 cycles) under power before fracture.

Because of the ongoing investigation into the FMS separation that occurred on ESN 956-121 at Charleston, GE developed and validated a field ultrasonic (UT) inspection to scan the forward end of the FMS under the threads where the fracture occurred from the forward side of the engine. These inspections were performed on all GENx FMS in the field and in storage. On August 13, 2012, another GENx-1B engine, ESN 956-175, installed on a 787-8 airplane that had not yet flown was found to have an indication of a similar crack in the FMS.

Like ESN 956-121, this engine had not been operated in flight. The fan midshaft had undergone 106 days of total time clamped to the adjacent components and no hours under power before detection of the crack indication. The engine was removed from the airplane and shipped to the GE Aviation facility in Durham, North Carolina, for disassembly with a total clamp time of 114 days. Further ultrasonic tests confirmed the crack indication. The FMS was removed from the engine and shipped to GE in Cincinnati for further inspection and examination.

3.2. Cincinnati Group Examination

The failed shaft, a second cracked shaft, and an exemplar shaft were inspected, non-destructively, and destructively at the GE Aviation engine facility in Evendale, Ohio near Cincinnati. The following metallurgical group representatives were present for at least part of the investigation:

- Erik Mueller, NTSB
- Wesley D. Pridemore, GE Aviation
- Walt Buttrill, GE Aviation
- Dale Weires, The Boeing Company
- Jim Kachelries, The Boeing Company
- Terry Khaled, FAA

The forward end of the fan midshaft arrived separate to the GE Evendale facility before the rest of the GENx engine 956-121 arrived. This engine was disassembled under the direction of Jim Hookey, NTSB AS-40, in order to observe and document other damage to the engine while the metallurgical group analyzed the fan midshaft fracture. As the investigation took place, several specimens were sent to outside labs for further testing. The results of this analysis are detailed below in Section 3.3.

3.3. Testing Procedures and Results

A variety of testing methods was used to inspect for conformance to specifications and internal standards of GE. The test results were compared and contrasted to the observations from the fractured 956-121 fan midshaft and the cracked

and intentionally opened 956-175 fan midshaft. Unless otherwise stated, all tests were performed at GE Aviation facilities in Evendale, Ohio.

3.3.1. Chemical Testing

Bulk hydrogen analysis was performed at ATI Specialty Materials in Monroe, North Carolina.² Specimens were excised from both fan midshafts near the forward spline sections. The testing was performed using a LECO inert gas fusion process. The tests revealed that the bulk hydrogen content of the fractured shafts was less than the maximum specification allowance.

A cellulose acetate replicating tape was placed on the 956-121 fracture surface after crack opening in order to determine if any contaminants present inside the crack were still on the surface. The acetate tape was placed on the crack surface, removed, and then rinsed with methanol to remove loose debris. The acetate tape was inspected using energy dispersive X-ray spectroscopy (EDS) to inspect for the presence of metallic elements. EDS found molybdenum, antimony, and phosphorus. Molybdenum and antimony are constituents in the Everlube 9002 dry film lubricant, and phosphorus is found in the synthetic engine oil used to assemble the engine.³ Fourier transform infrared spectroscopy (FTIR) discovered esters consistent with engine oil in the rinsed mixture.⁴

The forward face of the opened ESN 956-175 crack and the aft face of the ESN 956-121 fracture surface were each rinsed with methanol. The methanol was allowed to evaporate, and the residue was inspected using EDS. The residue contained elevated levels of molybdenum, antimony, sulfur, and phosphorus. Molybdenum and antimony are present in constituents in the Everlube 9002 dry film lubricant. Phosphorus and sulfur are elements found in constituents of the synthetic engine oil used in assembly of the engine. No other foreign contaminants were observed via this method. Organic constituents identified by FTIR inspection of rinse products obtained from the FMS fracture surfaces were consistent with identifiable organic constituents comprising in exemplar samples of the dry film lubricant, graphite grease, or synthetic engine oil used in assembly of the engine. No organic constituents were present in the methanol rinse of the FMS fracture surface that could not be associated with these components.

Isopropyl alcohol was used during the assembly of the engine. One of its applications was for cleaning surfaces of the fan midshaft and forward lock nut before application of the dry film lubrication. Using a wet chemical method, the water content

² ATI Specialty Materials, formerly Allvac, was the manufacturer of the GE1014 ingots used in manufacture of the fan midshafts. The ingots were produced by a vacuum induction melting followed by vacuum arc remelting process.

³ Everlube 9002 is a heat-cured, lead-free, molybdenum disulfide solid film lubricant used at temperatures below 700°F produced by Everlube Products, Peachtree City, GA.

⁴ FTIR characterizes the interaction of materials with infrared radiation to determine structures of organic and inorganic compounds by identifying vibrational and rotational energies associated with molecular bonds.

of the isopropyl alcohol was inspected. The content was found to be below the maximum limits in the specified material specifications.

A series of cured Everlube 9002 and cured MolyDag 254 coated titanium and stainless steel sheet specimens were exposed to high humidity at room temperature to determine the gravimetric hygroscopic absorption tendencies for each dry film lubricant.⁵ The specimen test exposure times were 84 and 108 hours. The weight gain of the Everlube 9002 specimens was more than 3.5 times greater than the MolyDag 254 specimens. Based on weight gain, the percentage of water absorption was found to be proportional to average Everlube 9002 coating thickness of the specimen.

Glow discharge mass spectroscopy (GDMS) was used to determine the chemistry of the fan midshaft material of both engines (956-121 and 956-175). Both fan midshafts conformed to the material chemistry of the prescribed GE1014 ultrahigh strength steel.⁶ In addition, supplementary methods were used to determine if any other trace elements were present in excess of the requirement. Carbon content was inspected using combustion infrared detection per ASTM E1019-11, oxygen and nitrogen content were inspected by inert gas fusion per ASTM E1019-11, and hydrogen was tested using vacuum hot extraction per ASTM E146-83. All other elements were inspected using direct current plasma emission spectroscopy per ASTM E1097-12. No trace elements were found above the material specification requirements.

X-ray diffraction (XRD) was used to determine the percentage of retained austenite in the fan midshaft material for both engines—ESN 956-121 and ESN 956-175. The tests were performed at Lambda Tech in Cincinnati, Ohio. All samples exhibited the same percentage of retained austenite, which was identical to control GE1014 specimens. This percentage was within drawing requirements for the fan midshaft material.

Electron microprobe analysis (EPMA) was used to determine if the fan midshaft metallurgical cross-sections exhibited significant alloy segregation in different locations of the cross-section, as defined per GE specifications. No evidence of alloy segregation was found.

3.3.2. Mechanical Testing

Room temperature tensile test results were conducted on specimens removed from near the splined regions of ESN 956-121 and ESN 956-175 fan midshafts. The specimens from ESN 956-121 were tested at room temperature per ASTM E8 and at 400°F after a 30 minute soak time per ASTM E21. Both tests showed the 956-121 fan

⁵ MolyDag 254 was a dry film lubricant used in other GE engine assemblies, manufactured by Henkel Corporation, Madison Heights, MI. This lubricant was replaced by Everlube 9002 and was not used in the GENx engine in part due to its lead-based constituents.

⁶ GE1014 is a type of ultrahigh duplex strengthened steel developed for applications requiring high yield strength and fatigue properties, developed by General Electric. *M.A. Rhodes, E.L. Raymond, W.M. Garrison, High Strength, High Fatigue Structural Steel. US Patent 5,393,488 filed August 6, 1993 and issued February 28, 1995.*

midshaft met or exceeded the requirements for ultimate tensile strength, 0.02% yield strength, elongation, and reduction of area. The specimens from ESN 956-175 were tested at room temperature per ASTM E8. All test specimens met specification requirements for ultimate tensile strength, 0.02% yield strength, elongation, and reduction of area.

Several test specimens of GE1014 were fabricated to replicate the stress concentration expected at the aft most thread root on the fan midshaft. Six of these tests were performed at GE Aviation and 12 more were performed at the Kobe Material Testing Laboratory at IHI Corporation in Tokyo, Japan.⁷ These tests applied the nominal and maximum static loads the specimen experienced on the fan midshaft aft most thread root after assembly and torquing (6026 lbs). The stress concentration factor (K_t) for these tests was 3.5.⁸

An additional dynamic load cycling to replicate fatigue loads expected on the shaft was applied (maximum load of 6572 lbs). Many of the specimens were coated with either Everlube 9002 or MolyDag 254 dry film lubricant, and either graphite grease or engine oil. These specimens were prepared by exposing them to 100% humidity environments for 7 days at room temperature prior to mechanical testing. As of the date of this report, all specimens have undergone at least 42000 cycles with 250 days exposure, with no specimens having fractured. Furthermore, all specimens have been inspected per magnetic particle inspection (MPI), with no crack indications found.

The specimens tested at IHI Corporation were then subjected to full tensile tests to determine if there was any loss of ultimate tensile strength. The specimens exhibited tensile properties acceptable for the FMS material, with no noted degradation of mechanical properties. The specimens tested at GE Aviation were retained intact for possible further examination later.

3.3.3. Metrology

Both of the fan midshafts were inspected at the GE QTC metrology laboratory to determine if the dimensions of the shaft conformed to the drawing. The primary instrument used to check the dimensions was a coordinate measuring machine (CMM). Several discrepancies were found with some of the dimensions on the forward spline section shape of the 956-121 shaft. No other discrepancies were found.

This spline section was then tested at Hunting Dearborn, Inc. in Fryeburg, Maine using Zeiss CMM instrumentation. No discrepancies were found after this inspection.

⁷ IHI is the manufacturer of the fan midshaft, among other components, for the GENx engine.

⁸ K_t is a multiplying factor for applied stress that allows for the presence of a structural discontinuity such as a notch and is equal to the ratio of the greatest stress in the discontinuity region to the nominal stress for the entire section.

3.3.4. Environmental Testing

One GE1014 stress corrosion cracking (SCC) bend specimen tested during prior alloy developmental studies (per ASTM G39) in salt water (NaCl) was made available for fractographic examination to compare with the incident FMS fracture surfaces, documented in *NTSB Materials Lab Report 13-086*.⁹ The SCC bend specimen fractured after 91.7 days of testing. The fracture surfaces of the SCC test specimen in both the uncleansed and cleaned conditions are shown in Figure 1. Both mating halves of the fracture surface remained discolored after cleaning. SEM examination of the test specimen revealed fewer corrosion products on the fracture surface, as illustrated in Figure 2. Figure 3 shows a transgranular fracture morphology with secondary surface cracking observed near the end of the SCC specimen crack consistent with fracture features observed on the fractured fan midshaft from ESN 956-121 (see *NTSB Materials Lab Report 13-086*). The innermost areas of the fracture without discoloration exhibited dimple rupture, indicative of overstress in the last cross-section of the specimen to fail (Figure 4). Cross-sections of the test specimen were produced, showing branched cracking consistent with stress corrosion cracks in high strength steels (see Figure 5). No evidence of chlorine was detected by EDS at the end of the progressive crack on the SCC test specimen fracture surface. Chlorine was found on the surface of the SCC specimen exposed directly to the NaCl environment.

Following the fracture of the fan midshaft in ESN 956-121 and the discovery of the cracks in the ESN 956-175, a series of 168 static two-point bend tests of the fan midshaft material were conducted in accordance with ASTM G39. The test specimens were tested in a humid bed inside a plastic container. The specimens were tested using a variety of iterations of coating material(s), to determine if any of the assembly constituents could lead to environmentally assisted cracking (EAC) of the fan midshaft material. The configurations included eight specimens (two held at 170 ksi, two held at 190 ksi, two at lab-controlled ambient humidity, two 95% humidity, all at 72°F) each of:

- Bare GE1014
- GE1014 with cured Everlube 9002
- GE1014 with uncured Everlube 9002
- GE1014 with uncured Everlube 9002 and graphite grease
- GE1014 with moistened, cured Everlube 9002
- GE1014 with moistened, cured Everlube 9002 and graphite grease
- GE1014 with moistened, cured Everlube 9002 rinsed with isopropyl alcohol and graphite grease applied
- GE1014 with cured Everlube 9002 and graphite grease
- GE1014 with cured Everlube 9002 rinsed with isopropyl alcohol and graphite grease applied with 185°F 8-hr bake
- GE1014 with cured Everlube 9002 and engine oil with 185°F 8-hr bake
- GE1014 with graphite grease with 185°F 8-hr bake

⁹ Stress corrosion cracking is a progressive failure mode of a susceptible material in a corrosive environment under sustained stress.

- GE1014 with cured Moly-DAG 254 with 185°F 8-hr bake
- GE1014 with cured Moly-DAG 254 and engine oil with 185°F 8-hr bake

Additional conditions were added to some of the test specimens including with and without isopropyl alcohol rinse. The specimens were configured to impart one of two static stresses meant to replicate field conditions.

As of the time of this report, two GE1014 specimens had fractured: one at 43 days with Everlube 9002 dry film lube and graphite grease, and the second at 149 days with the Everlube 9002 dry film lube and synthetic engine oil (both failed at the lower 170 ksi stress level and higher humidity). Figure 6 shows the fracture surface of the specimen that failed after 43 days. The fracture surface shows the rust-colored area consistent with environmental cracking that initiated at a corner on the tensile loaded surface of the specimen. The crack progressed until the remaining cross section failed from overstress. The fractured specimen showed similar fracture surface features to the previous stress corrosion specimen. However, there was a discernible corrosion product layer on the compressive-loaded side of the fracture surface, as depicted in Figure 7. This corrosion product exhibited blister morphology—these features contained minor levels of chlorine, as detected using EDS.

A GE1014 tensile specimen, notched 0.01 inch deep with a 0.01 inch root radius, was subjected to cathodic hydrogen charging conditions with no applied load. The experiment was performed to assess the resulting fracture morphology of a hydrogen embrittled GE1014 material. The charged specimens were subjected to charge voltages of 2.5 V versus a platinum foil counter electrode for 68 hours in 1 N sulfuric acid (H_2SO_4) solution at ambient temperature. Subsequent tensile tests demonstrated successful hydrogen charging of test specimen, showing a reduction in ultimate tensile strength (~60%) compared to control GE1014 specimens. SEM examination revealed an annular region of less ductile, transgranular fracture morphology adjacent to the notch as shown in Figure 8. The fracture morphology closely resembled that of the EAC regions of both event FMS fracture surfaces (Figure 8b). The inner area of the test specimen showed only dimple rupture, indicative of overstress (Figure 8c).

A second test with notched GE1014 specimens was performed under identical chemical conditions but was subjected to a 500 lb load in order to assess potential changes in hydrogen diffusion rates into the material. The specimens fractured during charging between 24 and 68 hours, exhibiting an increased percentage of fracture features consistent with hydrogen embrittlement. The rate of hydrogen diffusion was measured based on surface area of embrittlement relative to the time to fracture. The increased applied load resulted in increased hydrogen diffusion rates by a factor of 2 to 5 when contrasted with the unloaded specimen. The results of these tests showed the maximum hydrogen diffusion rate in the GE1014 material to be between $2 \times 10^{-8} \text{ cm}^2/\text{s}$ and $5.7 \times 10^{-8} \text{ cm}^2/\text{s}$. These rates were comparable to published diffusion rates of hydrogen in unloaded Aermet 100.¹⁰

¹⁰ Aermet 100 is an ultrahigh strength steel developed by Carpenter Technologies in Reading, PA.

Further corrosion studies on the fan midshaft material were performed at GRC. These tests measured relative corrosion performance (polarization resistance) per ASTM G59 and potentiodynamic polarization per ASTM G5. The materials tested were GE1014 and Marage 250, uncoated and coated with the two dry film lubricants (DFL), engine oil, and graphite grease in the following configurations:¹¹

- Bare GE1014
- Bare MAR 250
- GE1014 with Moly-DAG 254 DFL
- GE1014 with Everlube 9002 DFL
- GE1014 with Moly-DAG 254 DFL and engine oil
- GE1014 with Everlube 9002 and graphite grease
- MAR 250 with Moly-DAG 254 DFL
- MAR 250 with Everlube 9002 DFL
- MAR 250 with Moly-DAG 254 DFL and engine oil
- MAR 250 with Everlube 9002 and graphite grease

Relative corrosion performance was assessed using a polarization resistance technique. The specimens were 1 inch segments with a wire lead connected to one end of each specimen. The specimens were coated with an inert masking lacquer except for 1 cm² of area. Specimens were exposed to a cell containing a 5% salt (NaCl) solution under ambient temperature with ambient aeration, using a calomel reference electrode and a platinum counter electrode.

Polarization resistance revealed that bare GE1014 high strength steel exhibited a lower corrosion rate than Everlube 9002 DFL coated GE1014 high strength steel. Greater corrosion rates were also observed for Everlube 9002 DFL coated GE1014 and Marage 250 steels both with and without graphite grease. Synthetic engine oil applied to coupons significantly reduced corrosion rates as the oil was found to act as a dielectric barrier. Graphite grease applied to Everlube 9002 DFL coated GE1014 specimens did not substantially increase the corrosion rate. However, the graphite grease did not act as a corrosion barrier in the manner that the engine oil did in this experiment.

Erik M Mueller
Materials Research Engineer

¹¹ Marage 250 (MAR 250) is a high-strength maraged steel used for the fan midshaft in other high-bypass turbofan engine models. This alloy is also used in the forward lock nut in the GENx engine.

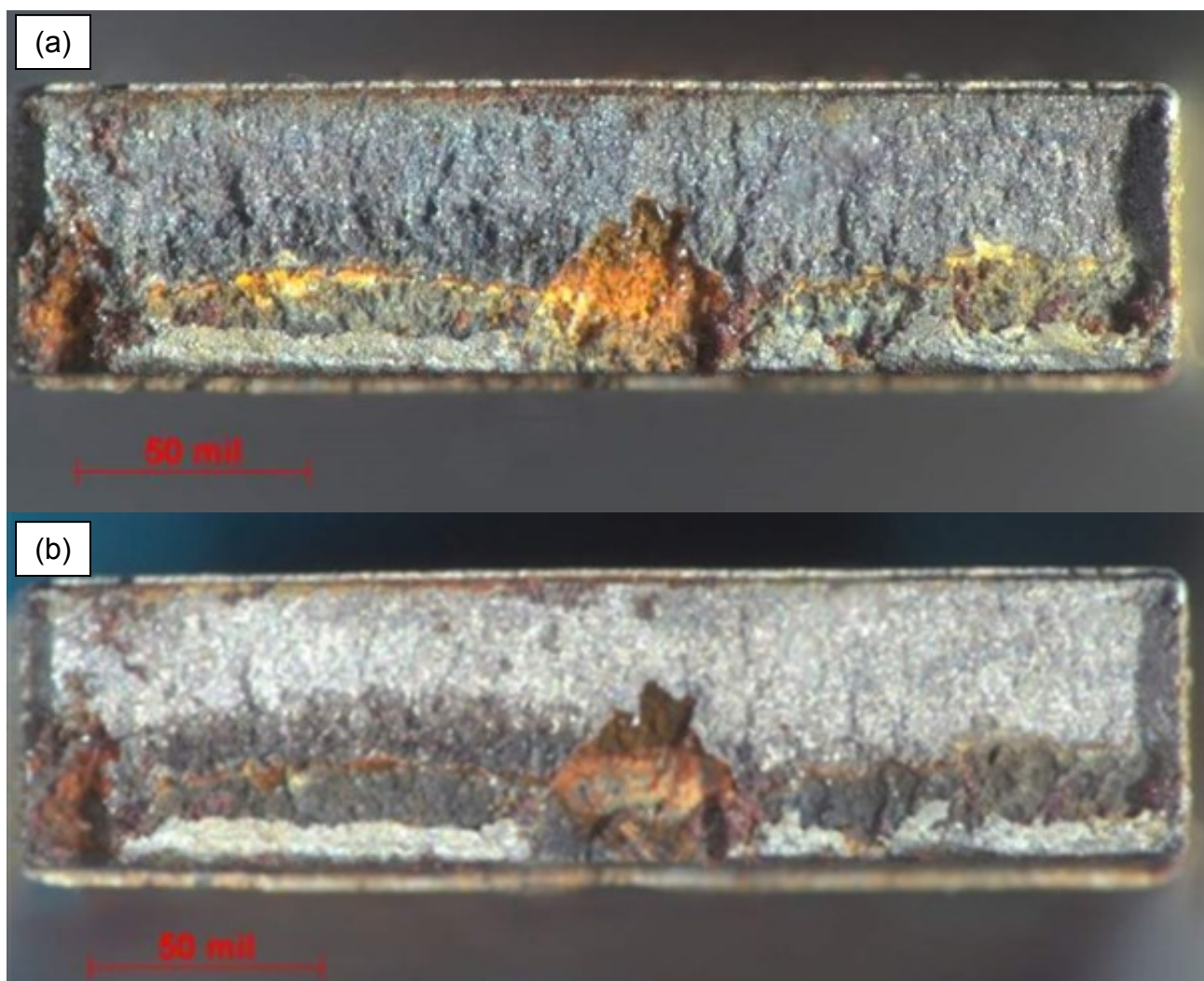


Figure 1 – Fracture surface of the developmental SCC sample (a) before and (b) after cleaning.

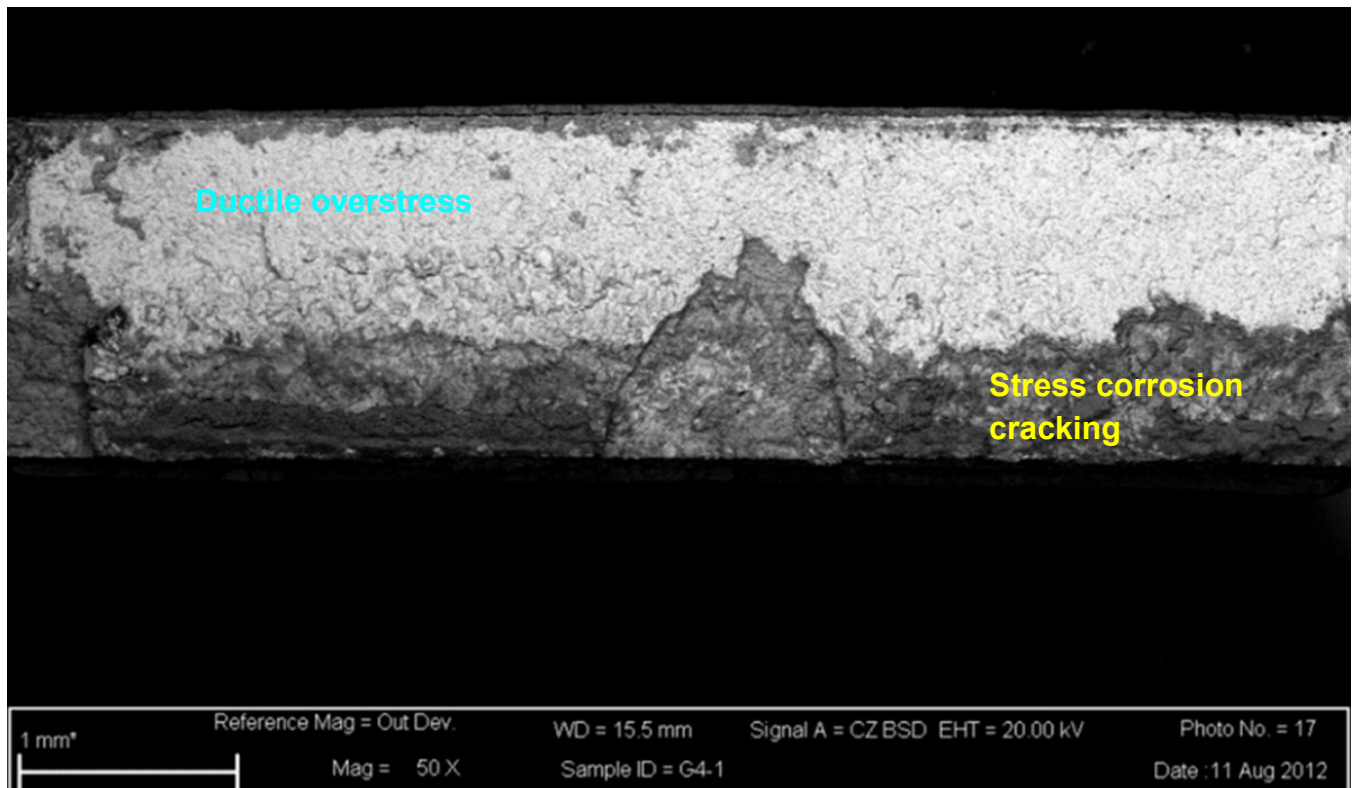


Figure 2 – Backscattered electron (BE) micrograph of the fracture surface in Figure 1. The darker areas are corroded and are indicative of stress corrosion cracking. The lighter areas, which are not corroded, indicate ductile overstress.

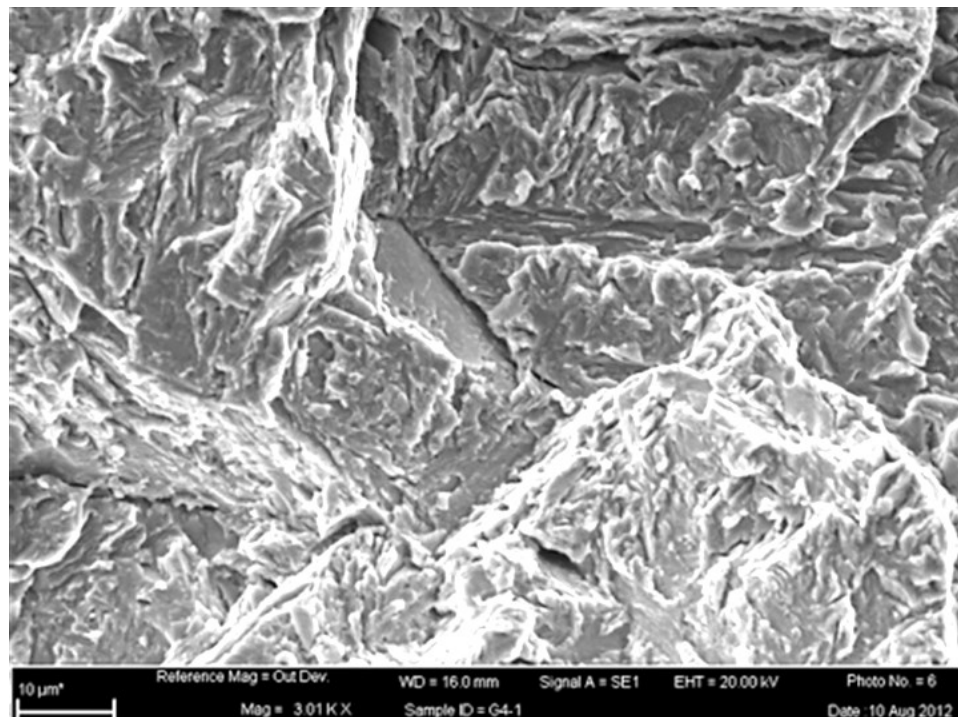


Figure 3 – Secondary electron (SE) micrograph of the fracture surface with stress corrosion cracking.

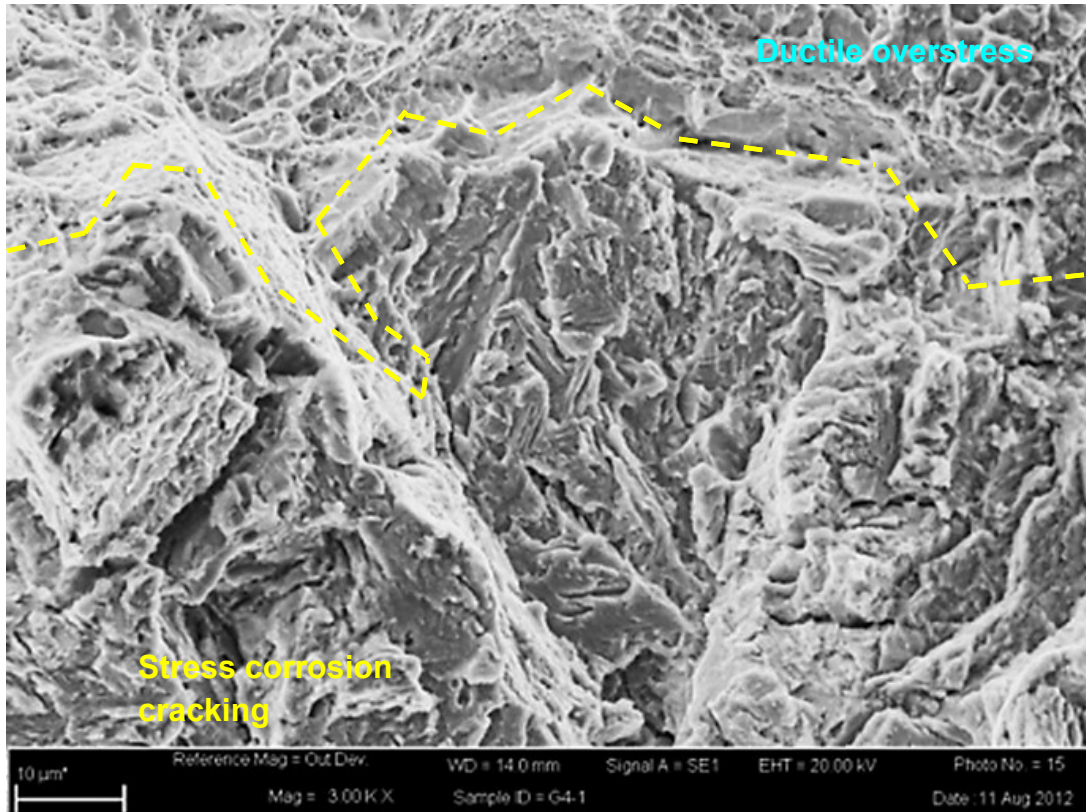


Figure 4 – SE micrograph of the transition from stress corrosion to overstress fracture.

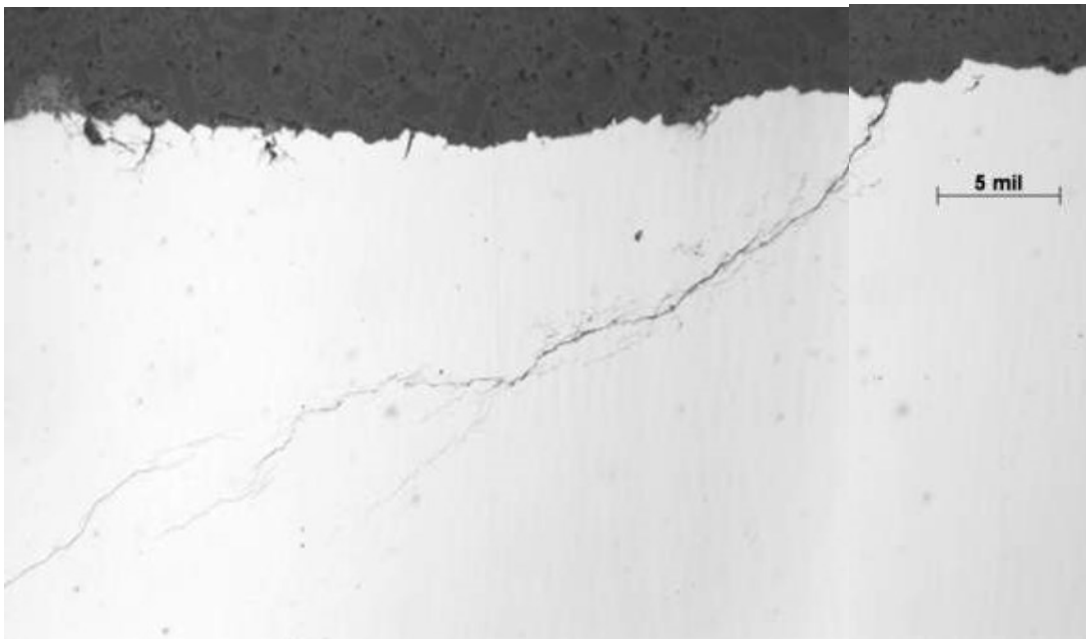


Figure 5 – Cross-section of a SCC specimen, showing branched secondary cracking indicative of SCC.

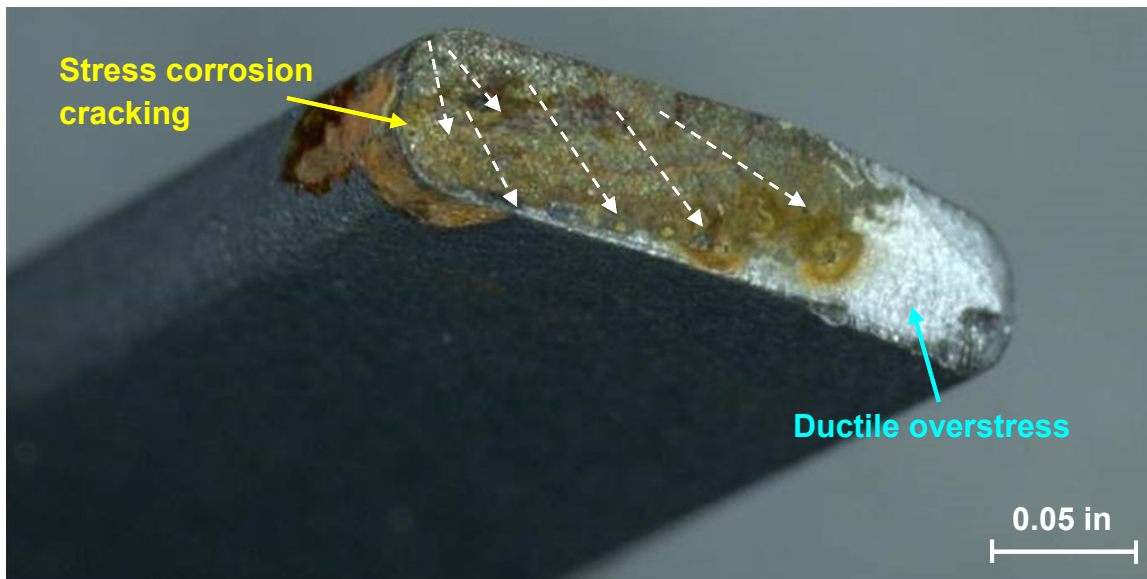


Figure 6 – Fracture surface of the stress corrosion specimen that failed after 43 days. The specimen shows a rust-colored region where the progressive stress corrosion crack grew from the specimen corner (white arrows denote crack growth direction).

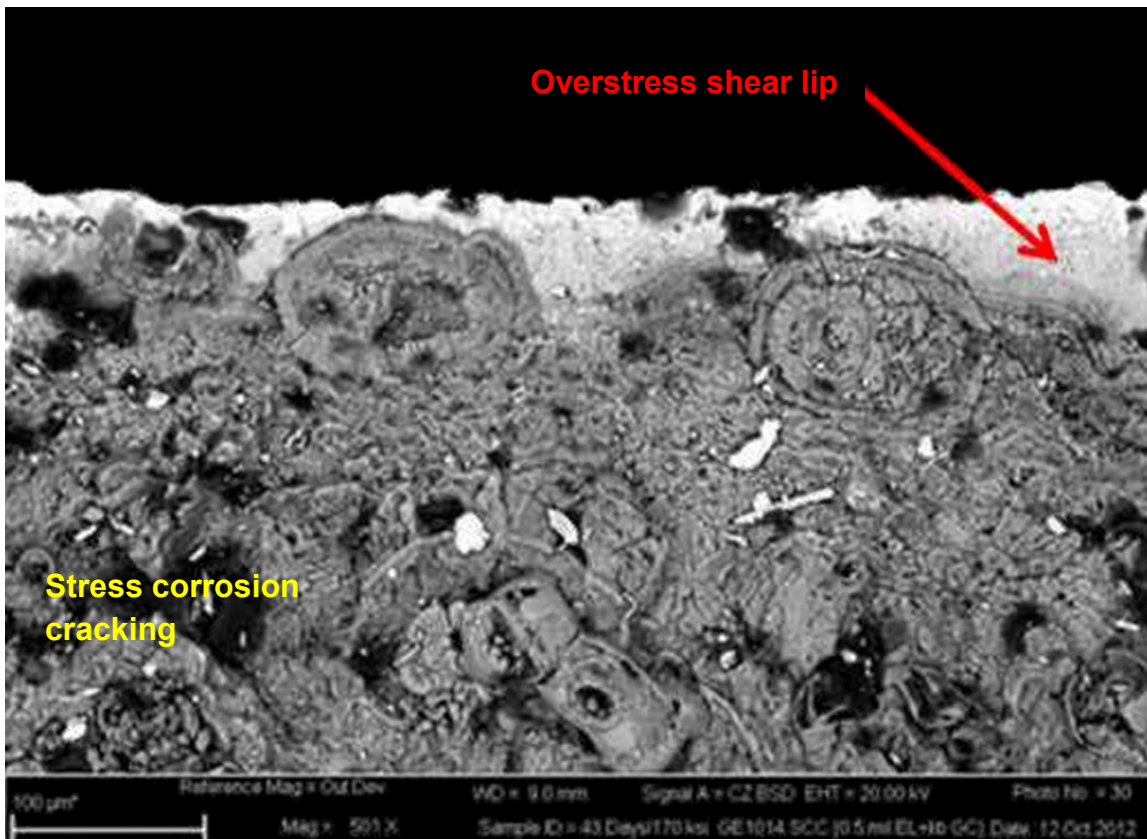


Figure 7 – BE micrograph of the stress corrosion specimen that fractured after 43 days, showing corrosion blisters near an overstress shear lip.

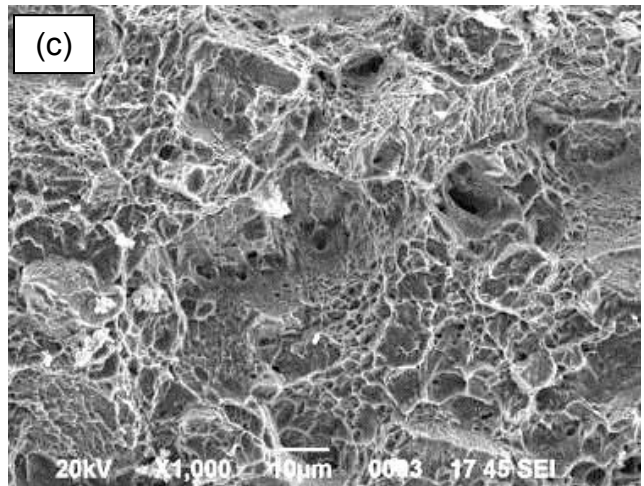
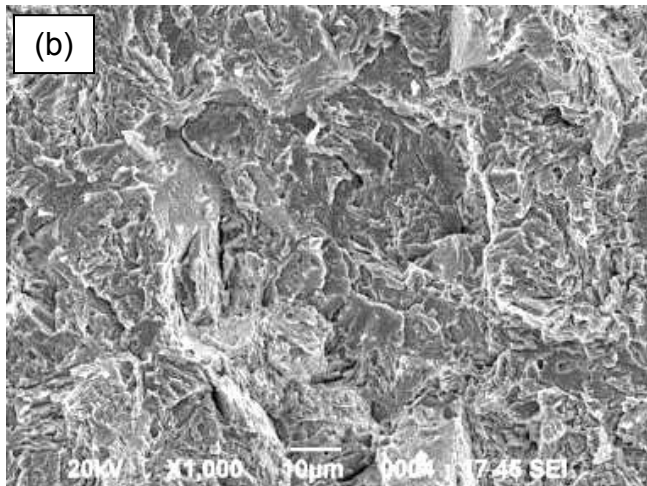
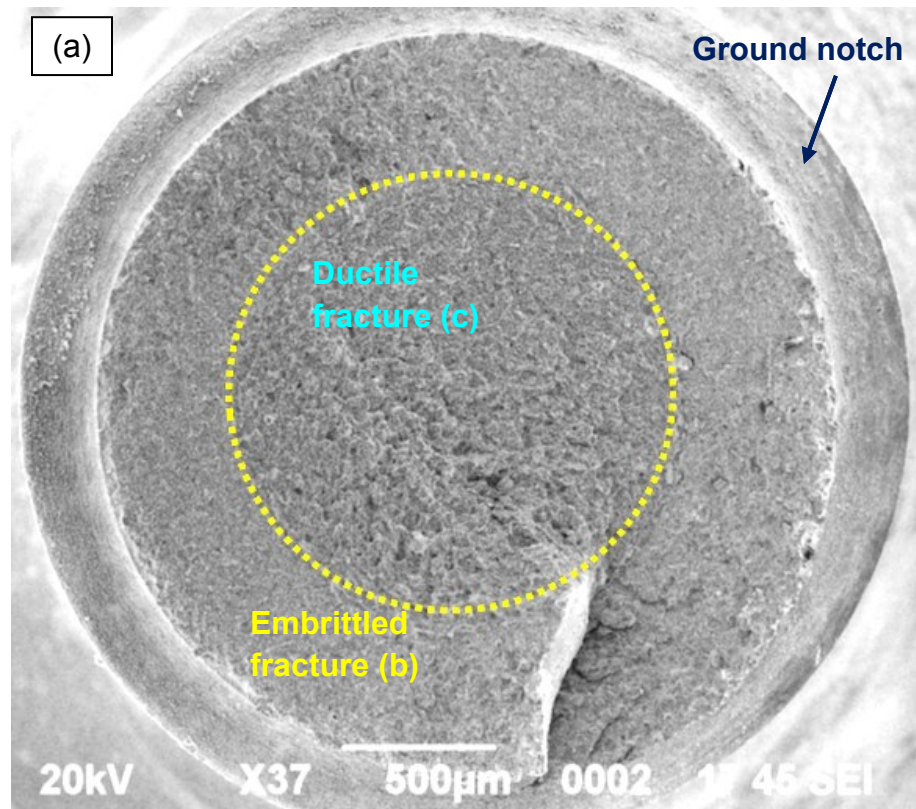


Figure 8 – The unloaded notched test specimen charged with hydrogen using H_2SO_4 showing (a) the overall specimen fracture surface with (b) an outer embrittled zone with cleavage-like transgranular fracture morphology and (c) the inner non-embrittled area showing only overstress dimple rupture.