Autofrettage Crack Growth in COPV liner Material

Jonas Merrell University of Utah

August 1st 2019

This work was supported by the NESC Materials TDT

Composite Overwrapped Pressure Vessel (COPV)

- Almost every space flight vehicle uses composite overwrapped pressure vessels (COPVs). These COPVs must be demonstrated to be resistant to crack damage.
  - Used to contain propellants and gasses at high pressures for many space vehicles
  - The interior is a metallic liner that serves as the container of the gas/fluid
  - The exterior is a composite overwrapping for strength

Problem statement

- Most COPVs undergo a initial proofing pressure called the autofrettage cycle. This yields the liner and leaves a compressive residual stress that is beneficial for resisting fatigue crack growth. The composite overwrap responds elastically.
  - Problem
    - Qualified analyses do not exist to predict the amount of crack growth during the autofrettage cycle
  - Approach
    - Conduct laboratory tests that simulate autofrettage loading and measure the amount of crack growth
  - Solution
    - Provide experimental data that could be used to characterize crack growth under autofrettage conditions for flight qualification of COPVs

COPV Qualification Requirements

- Demonstration of safe life
  - The COPV must survive the equivalent of 4 operational lifetimes with the largest crack that can be missed by the certified non destructive evaluation (NDE) method at the worst location
  - This can be demonstrated using numerical tools for elastically responding liners or experimentally for plastically responding liners
- Demonstration of leak before burst (LBB)
  - The COPV must not burst with a crack in the liner that is 10 times the thickness of the liner
  - This will allow leaking (depressurization) rather than an explosive failure

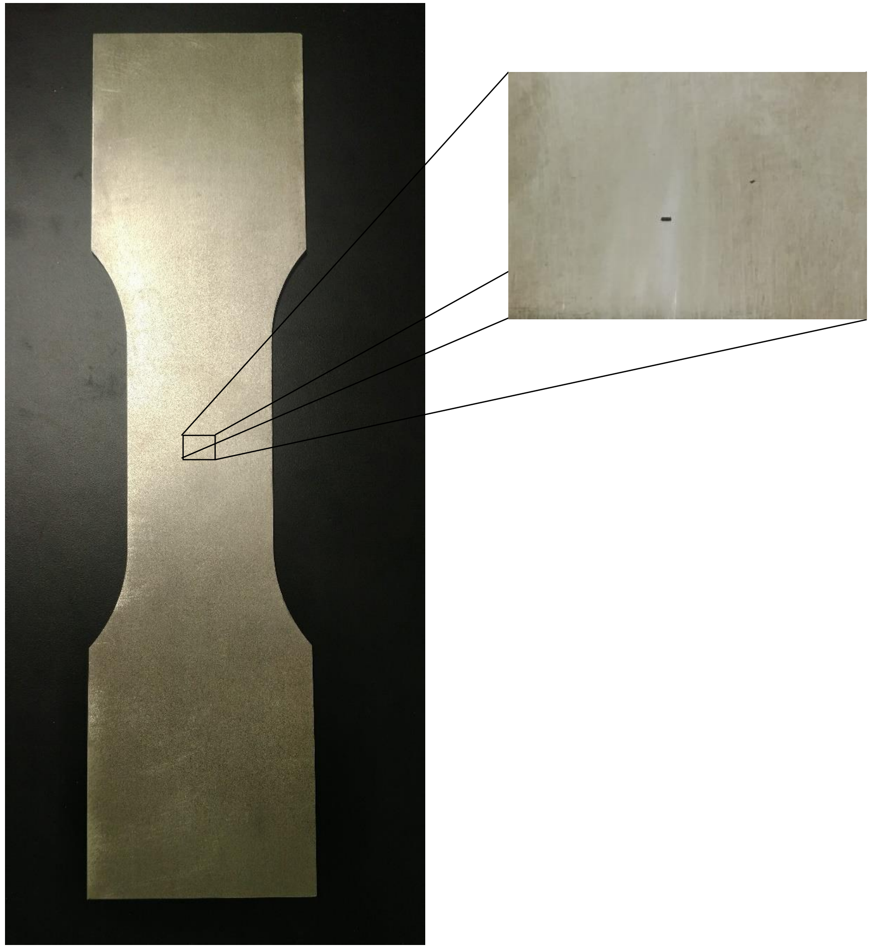
Objectives

- Characterize the amount of crack growth due to the autofrettage cycle for the metallic liner of a COPV

- Evaluate the influence of multiple autofrettage cycles to determine if the crack growth from a single autofrettage cycle times 4 is conservative relative to 4 consecutive autofrettage cycles

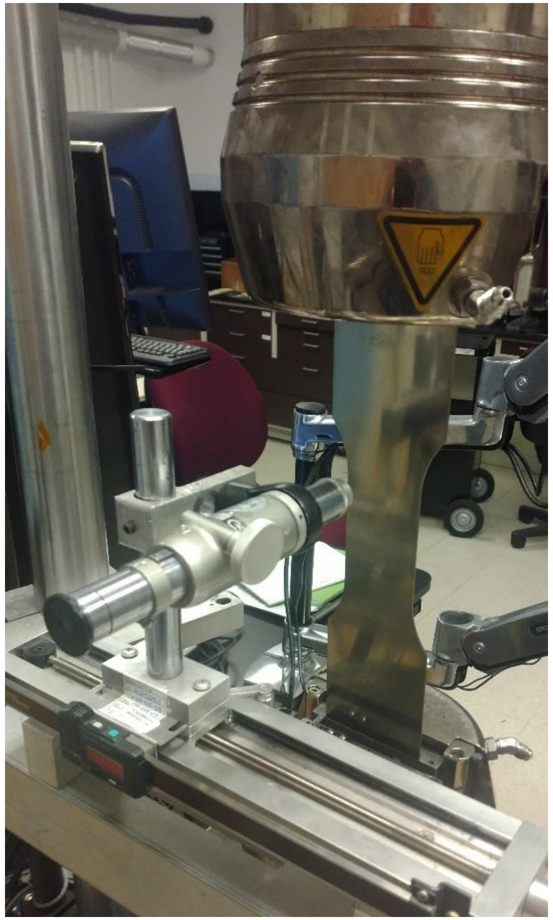
Testing

- Tests will be conducted on three common materials for COPV liners (aluminum, Inconel and titanium)
- Measurements of crack mouth opening displacement (CMOD) will be made for validation of future elastic-plastic analytical models
- The tests are conducted in 4 separate steps
  1. Pre-crack to mimic largest crack that can be missed by NDE inspection
  2. The autofrettage cycle is mimicked by loading the specimen in tension until a certain strain level.
  3. Fatigue to failure using a high R ratio (min/max stress)
  4. Obtain SEM images of the facture surface



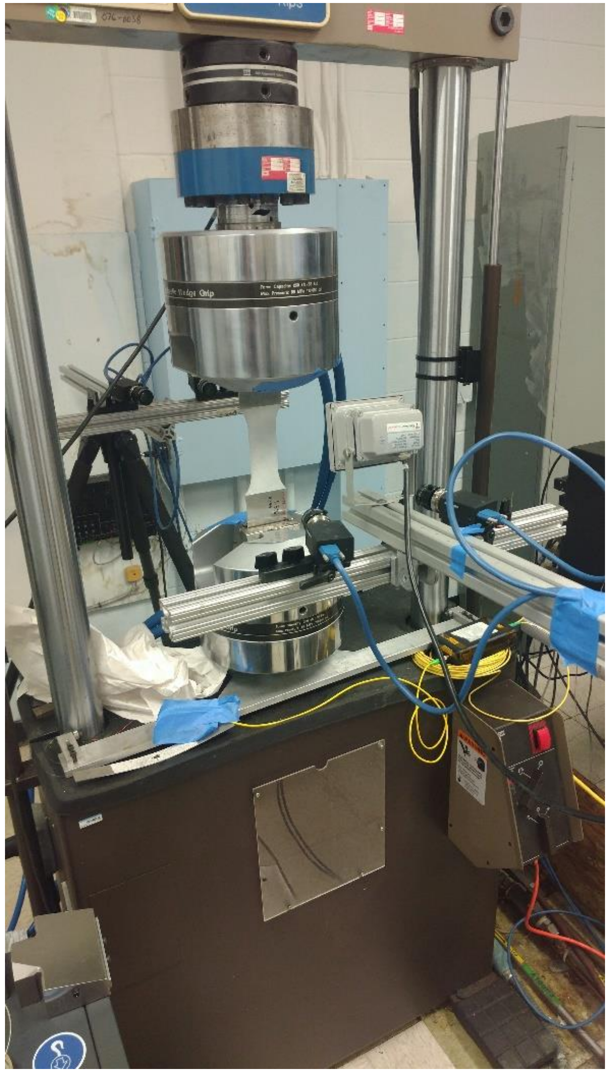
Pre-cracking

- Each specimen was notched to provide a stress concentration that will create a crack nucleation site
- Each crack was grown out to a length of 0.04 inches
- Crack length measured with a traveling microscope
- The specimens were pre-cracked at a stress level 80% of the material yield stress and at a stress ratio R=0.1



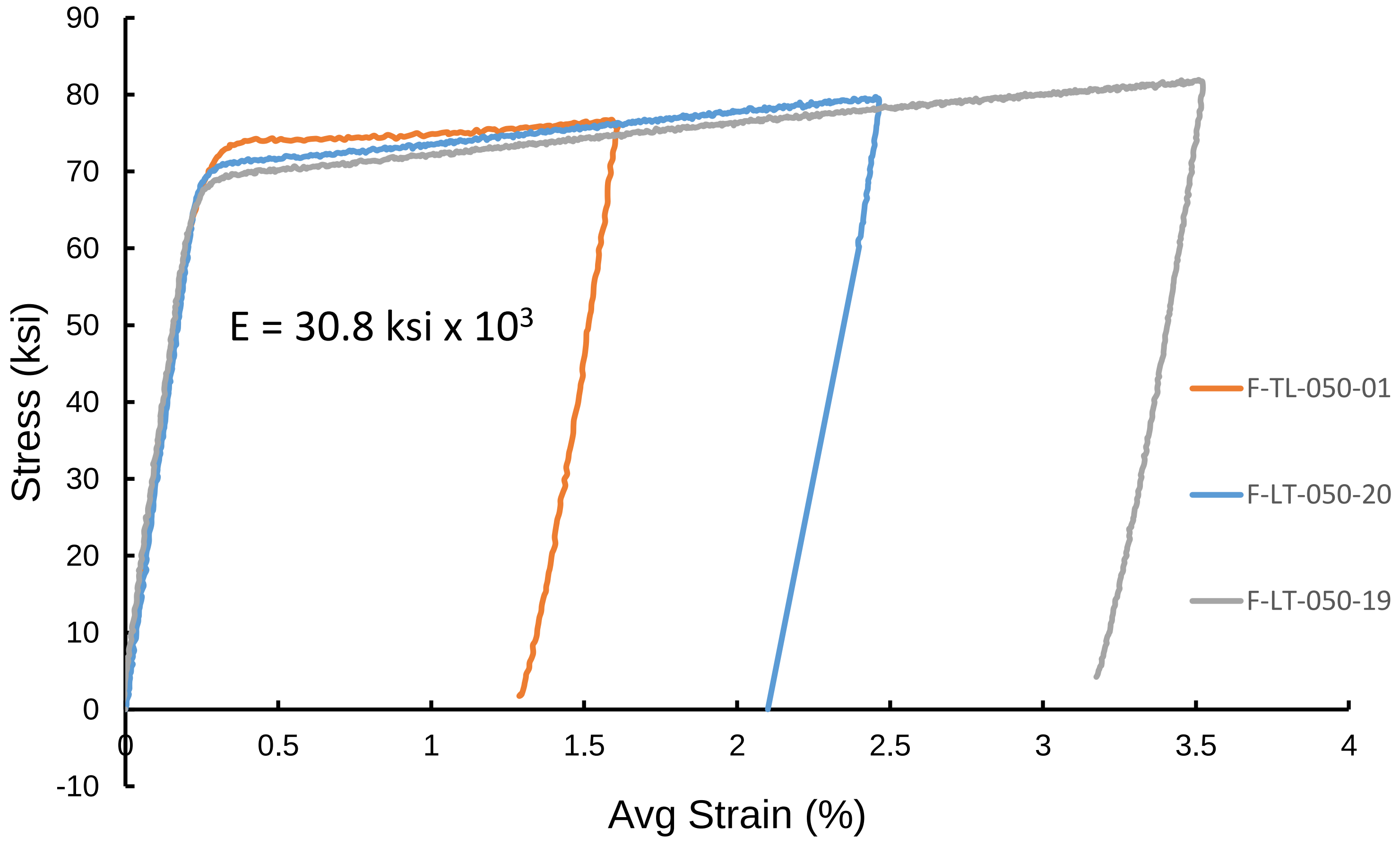
Single Autofrettage cycle

- The specimen is loaded in tension to a specified strain to simulate the autofrettage cycle.
  - The specimen is loaded in displacement control to the specified strain level
  - digital image correlation (DIC) is used to monitor the strain as the specimen is being loaded
- Materials tested to-date
  - Inconel 718 at 1.5%, 2.5% and 3.5% strain
  - Aluminum 6061-T6 at 1.5%, 2.0% and 2.5% strain
- After completion of the autofrettage cycle, the specimen is fatigued to failure at 80% of max load with an R ratio of 0.7



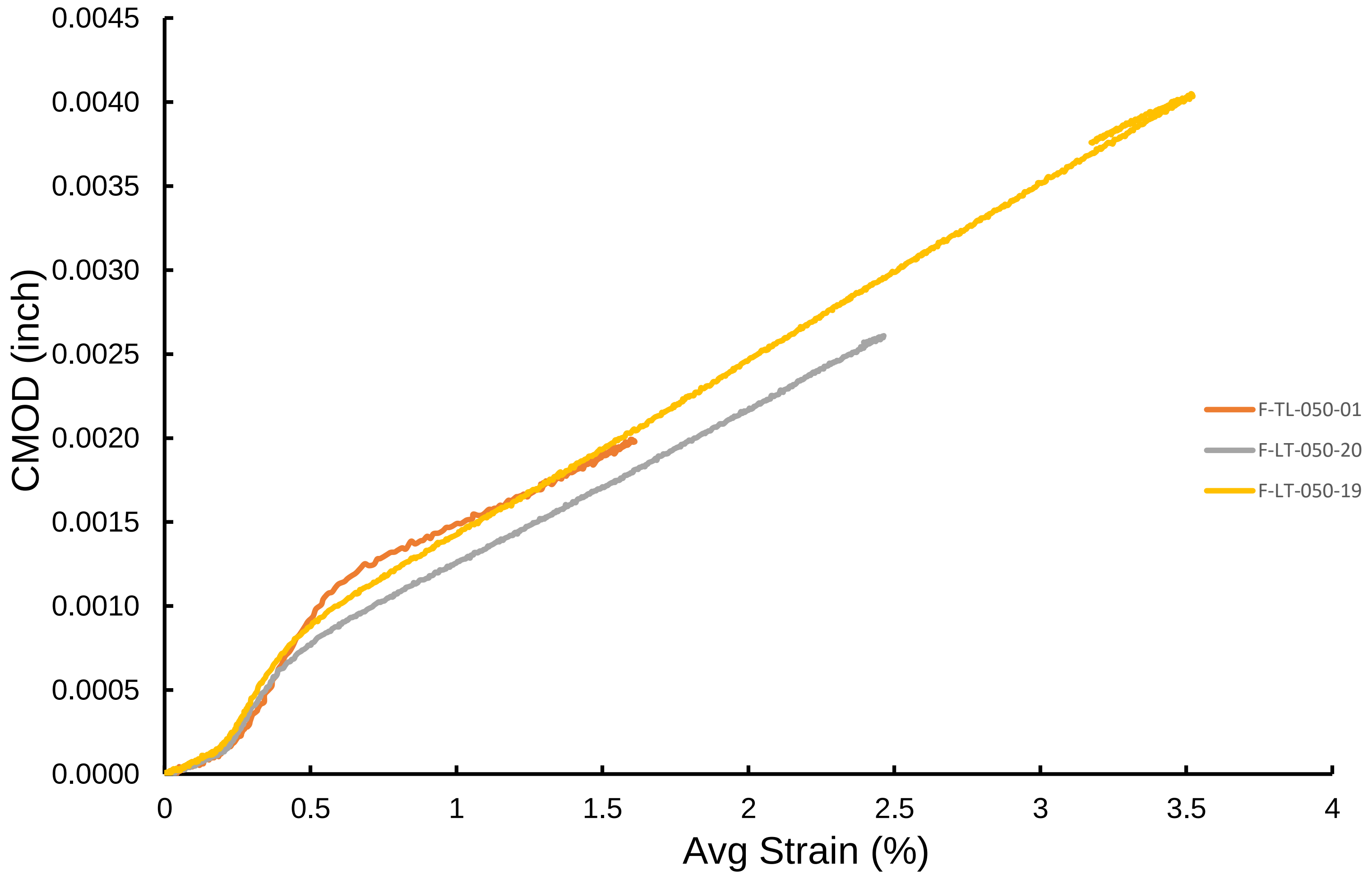
Single cycle 0.05 inch IN718

- Stress Strain curves for single cycle autofrettage tests
- Strain levels extracted from DIC data



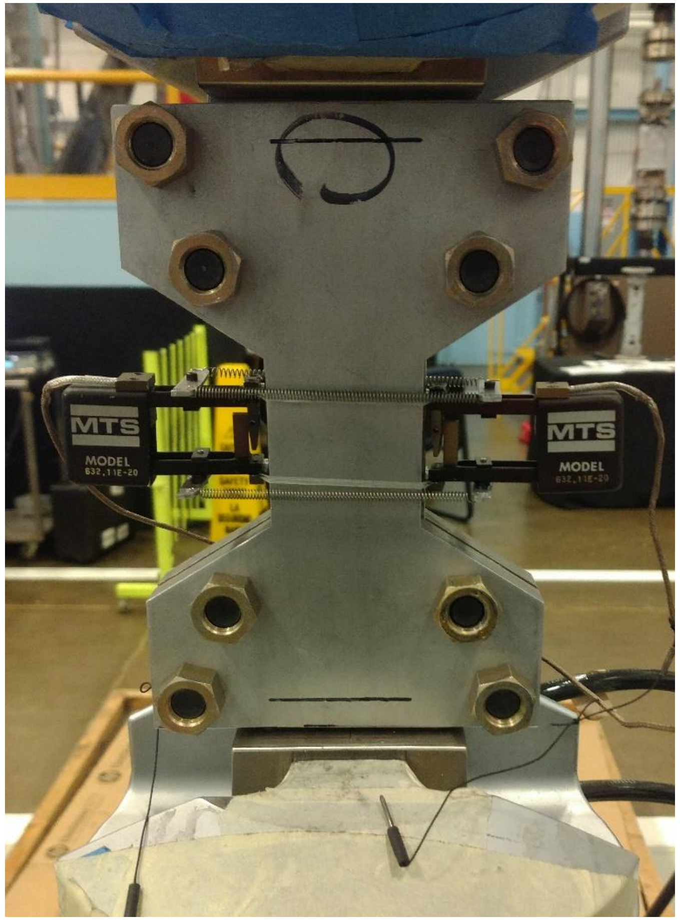
Crack Mouth Opening Displacement (CMOD)

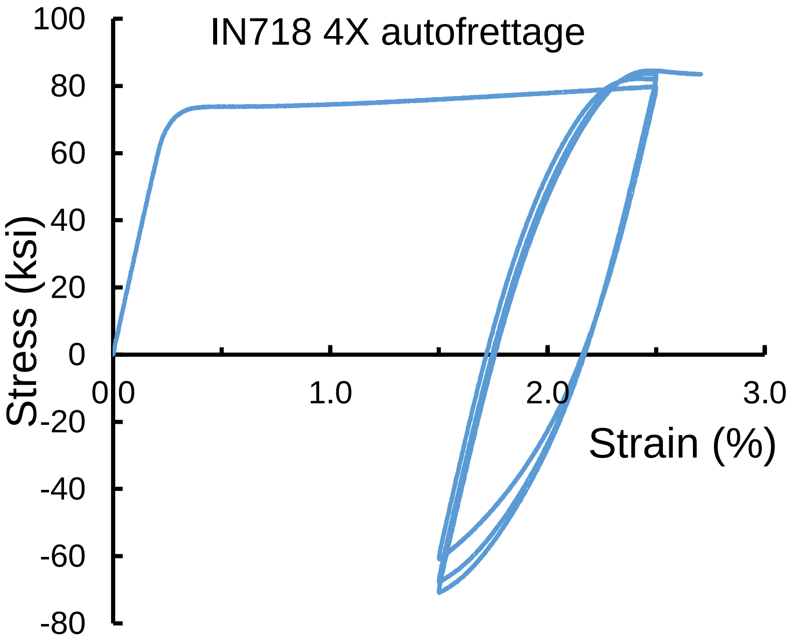
- CMOD for each autofrettage test from the 0.05 inch thick IN718 specimens
- CMOD is a indication of local behavior
- Used to validate future crack growth simulations



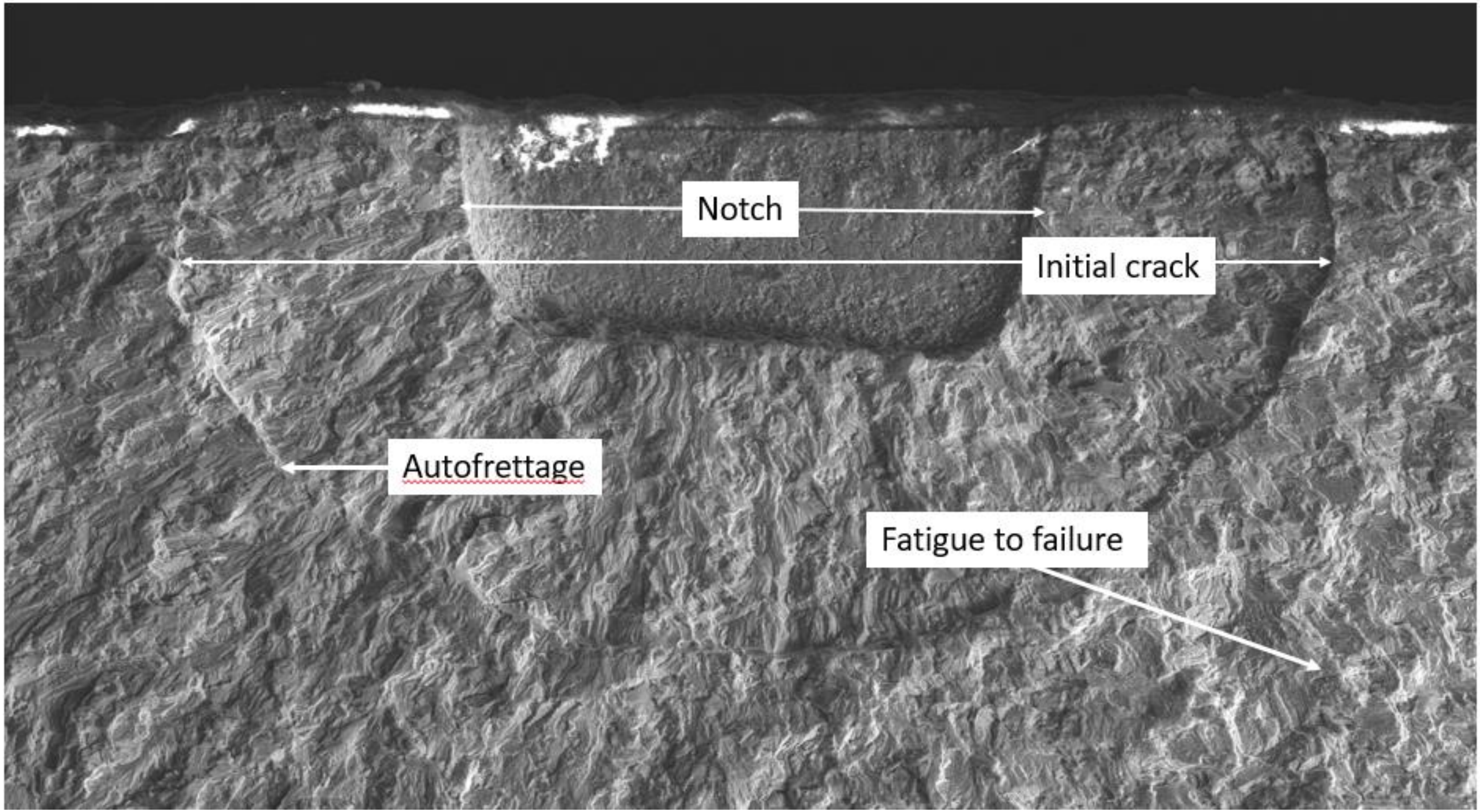
4X Autofrettage

- For the IN718 4 cycle autofrettage the strains cycled between 1.5% and 2.5%.
  - Going back to 1.5% required going into compression
  - Anti-buckling plates were used because of this DIC could not be used thus side mounted extensometers were used
- The specimens were loaded in high-R fatigue after the 4 autofrettage cycles (identical to that done on the single cycle tests)

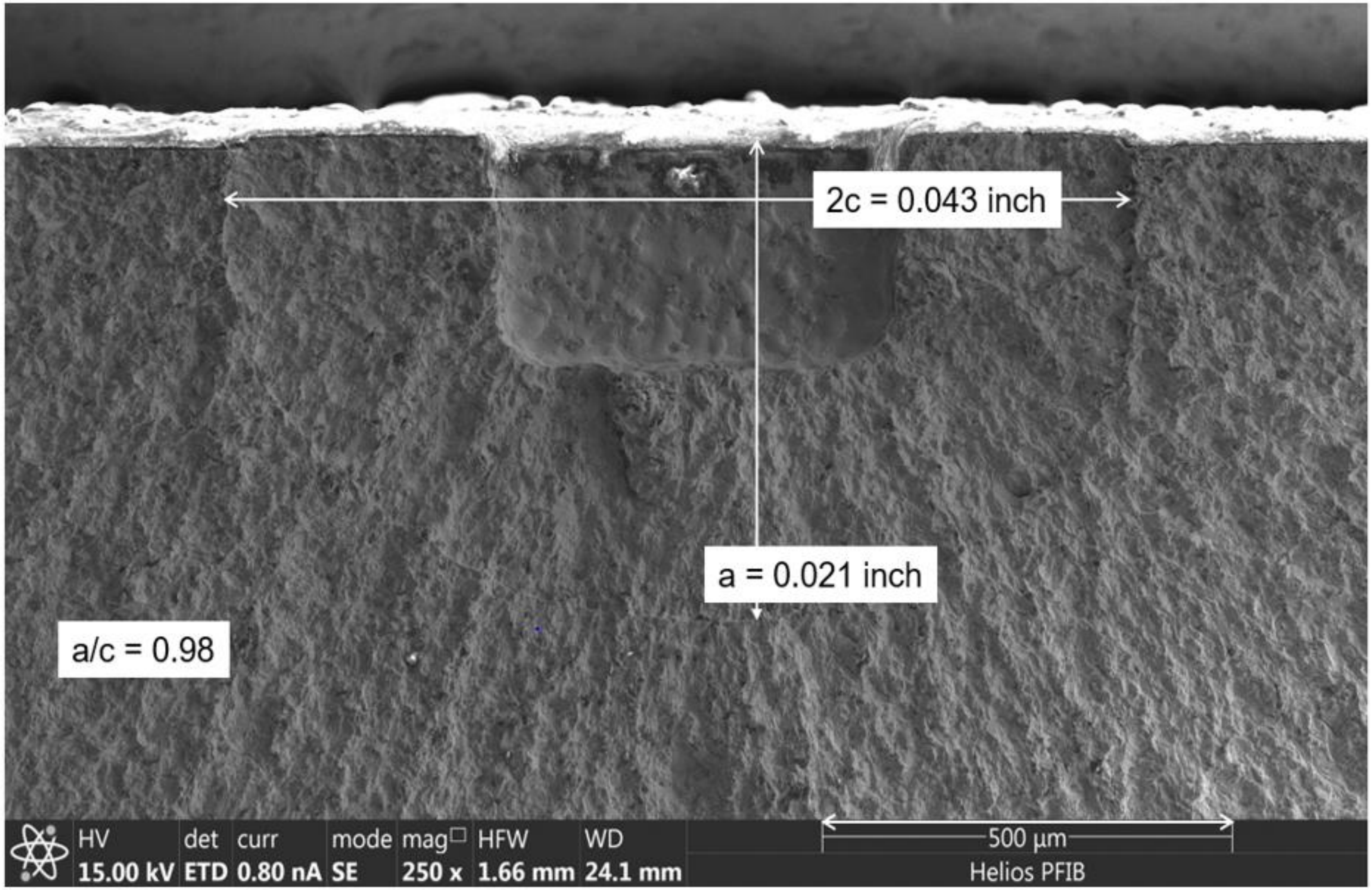




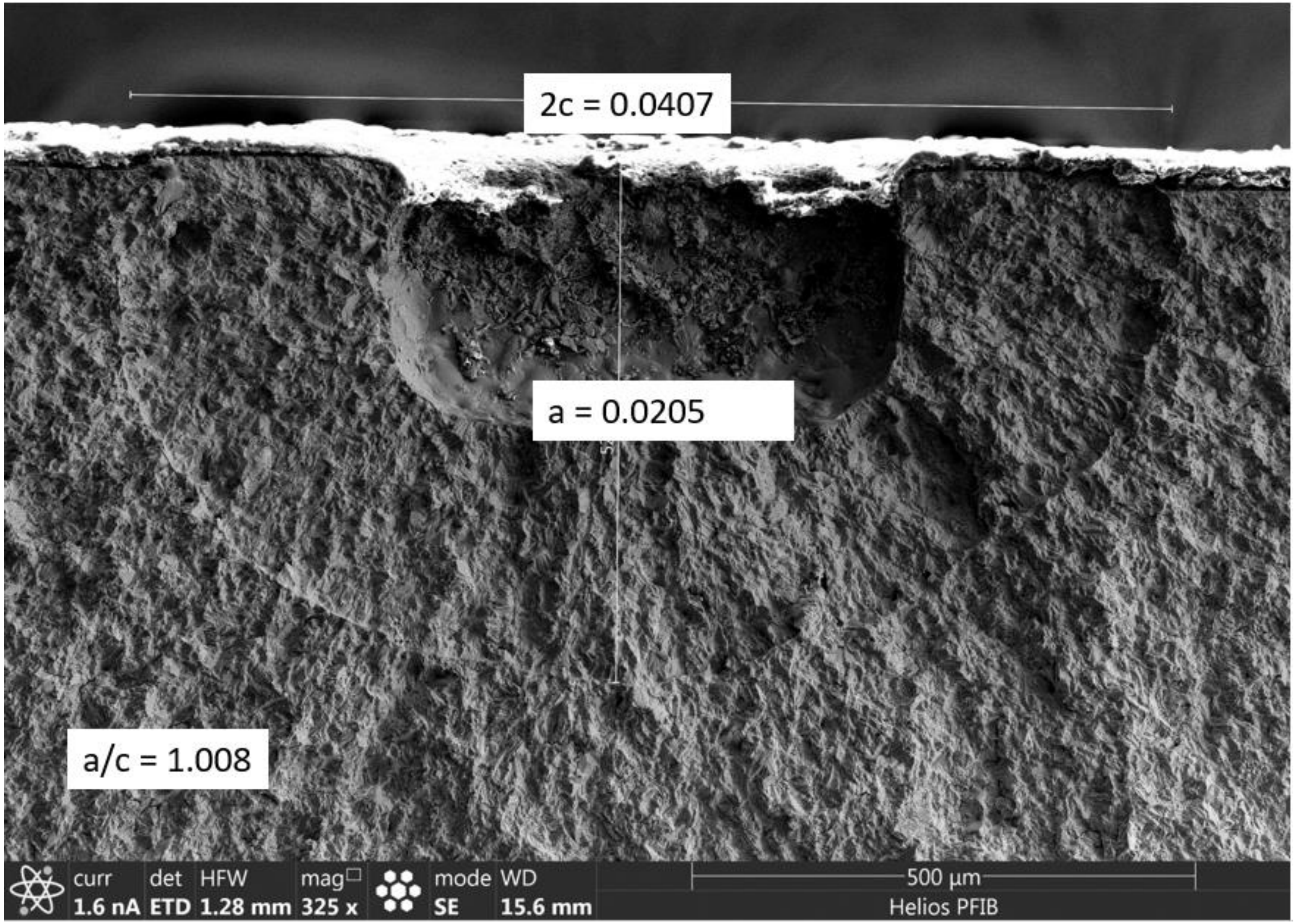
SEM image of fracture surface



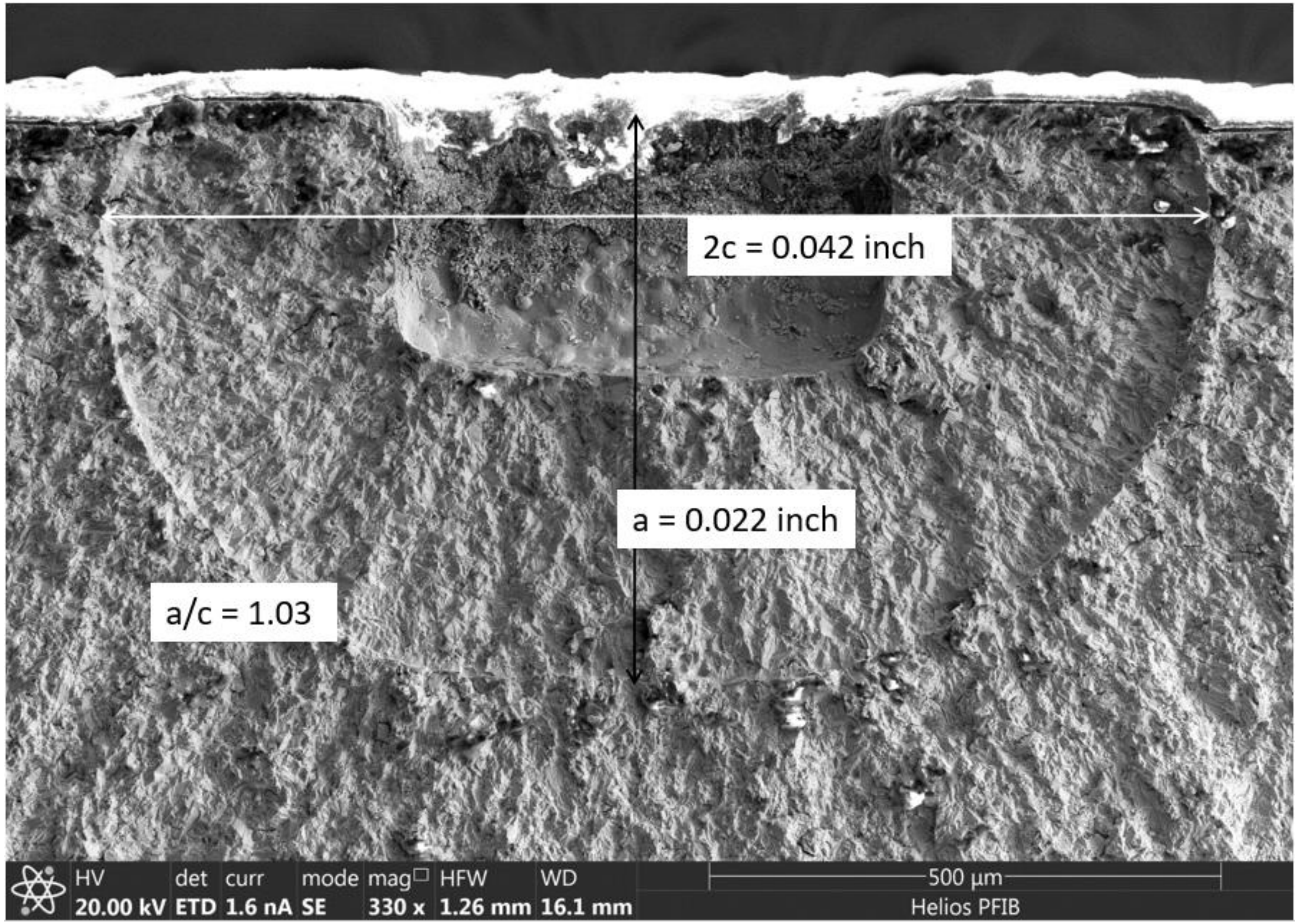
IN718 F-TL-050-01 w = 1.9975 t = 0.05 1.5%



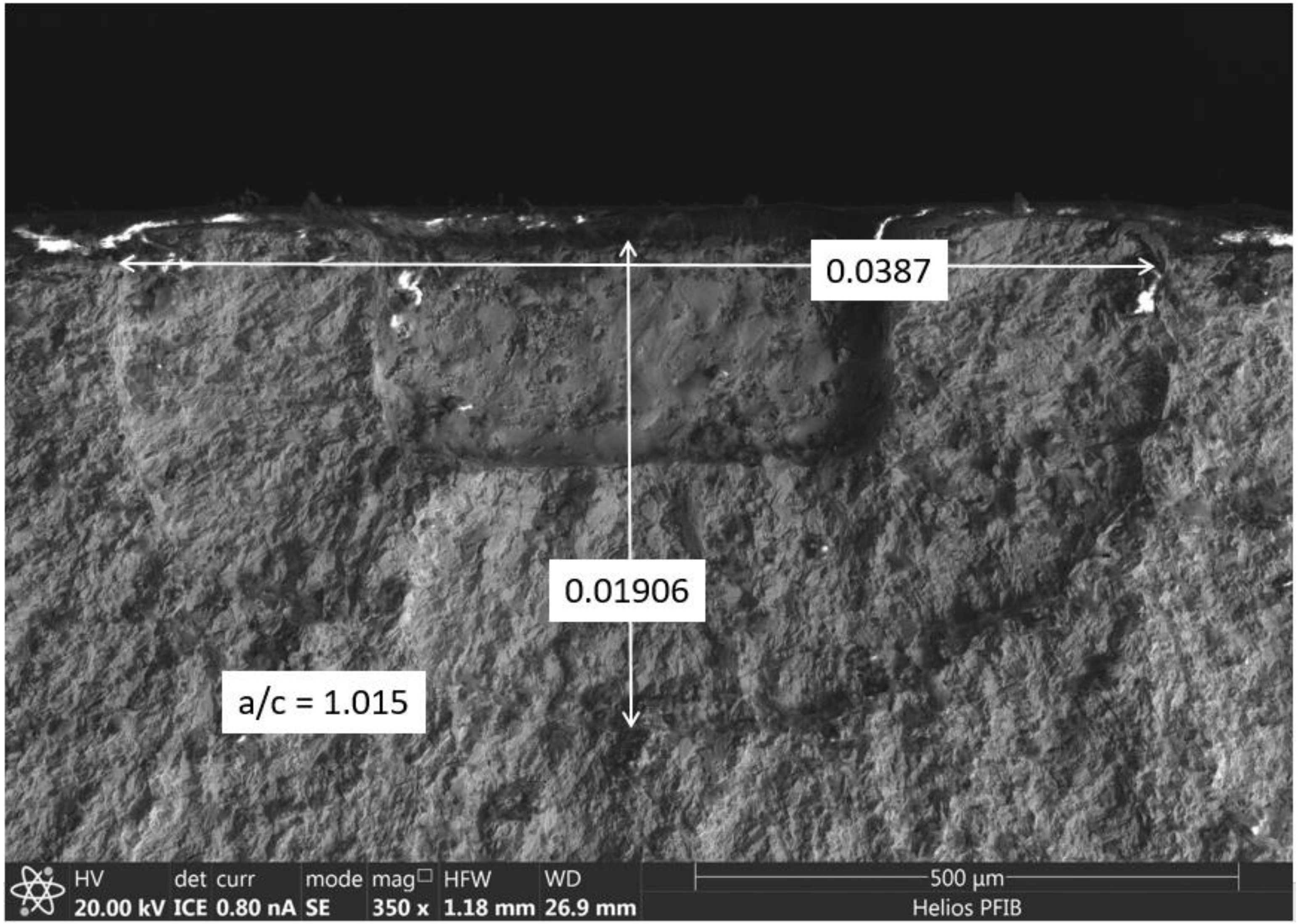
IN718 F-LT-050-20 w = 2.0035 t = 0.05 2.5%



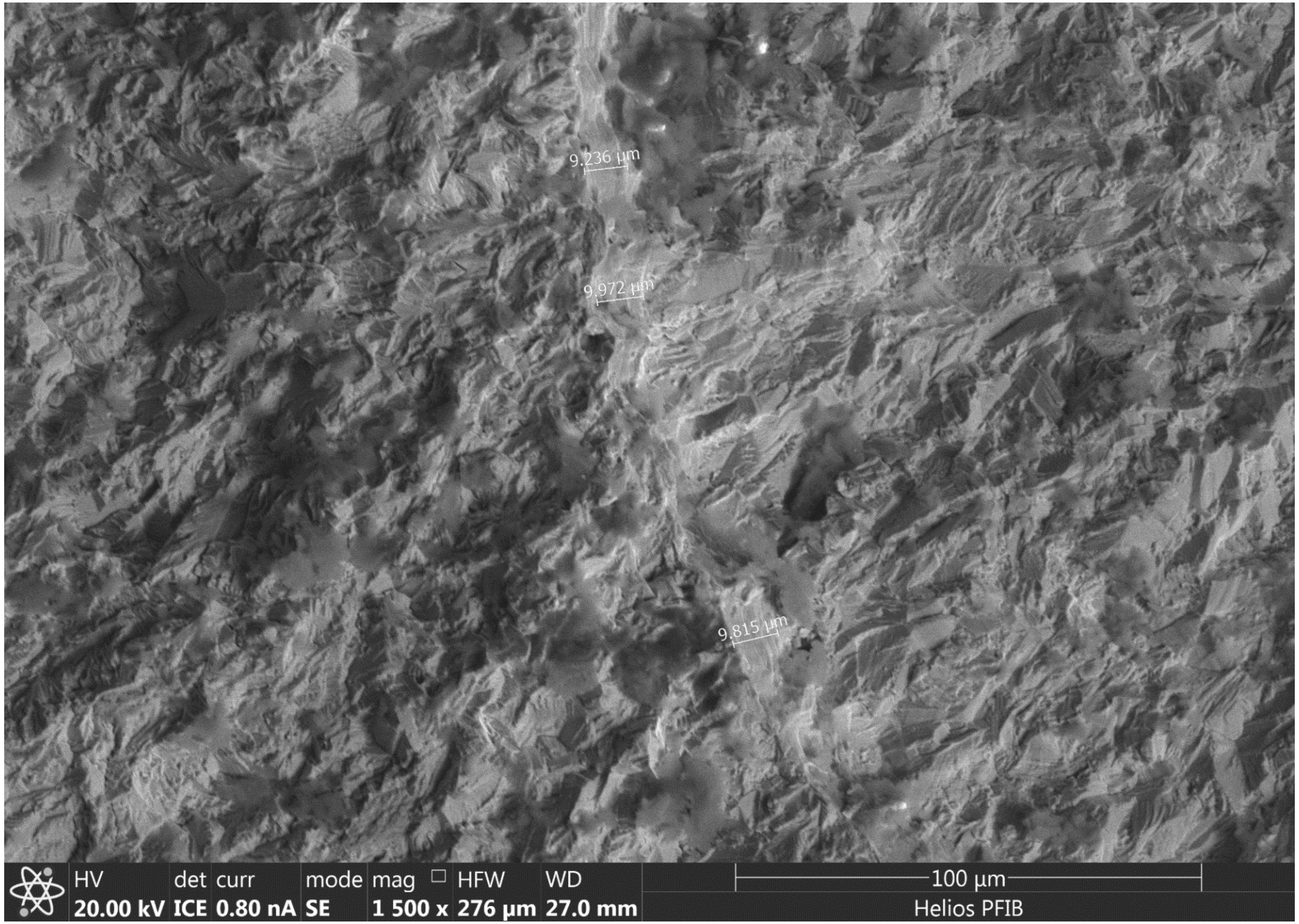
IN718 F-LT-050-19 w = 2.000 t = 0.051 3.5%



IN718 F-TL-050-02 w = 1.9985 t = 0.055 4X



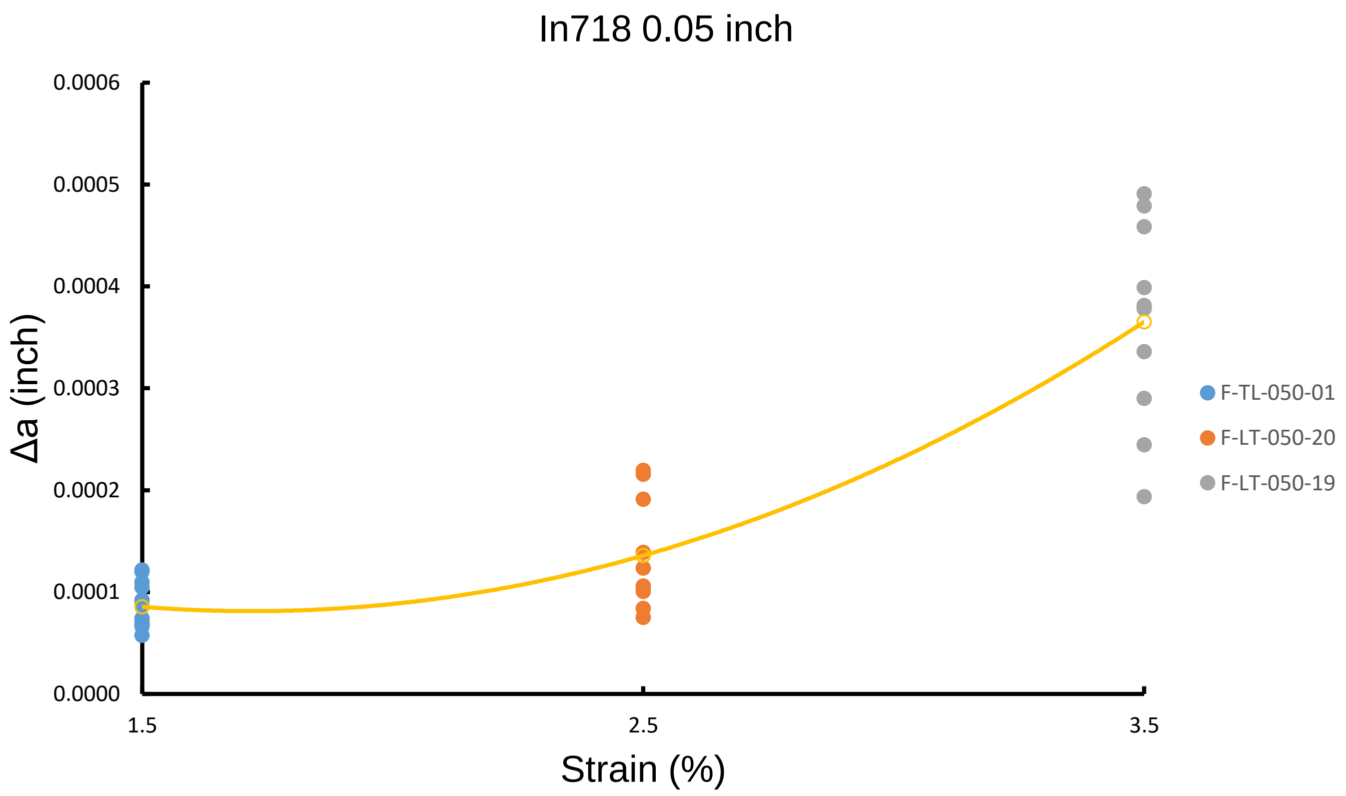
IN718 F-TL-050-02 w = 1.9985 t = 0.055 4X



Autofrettage crack growth

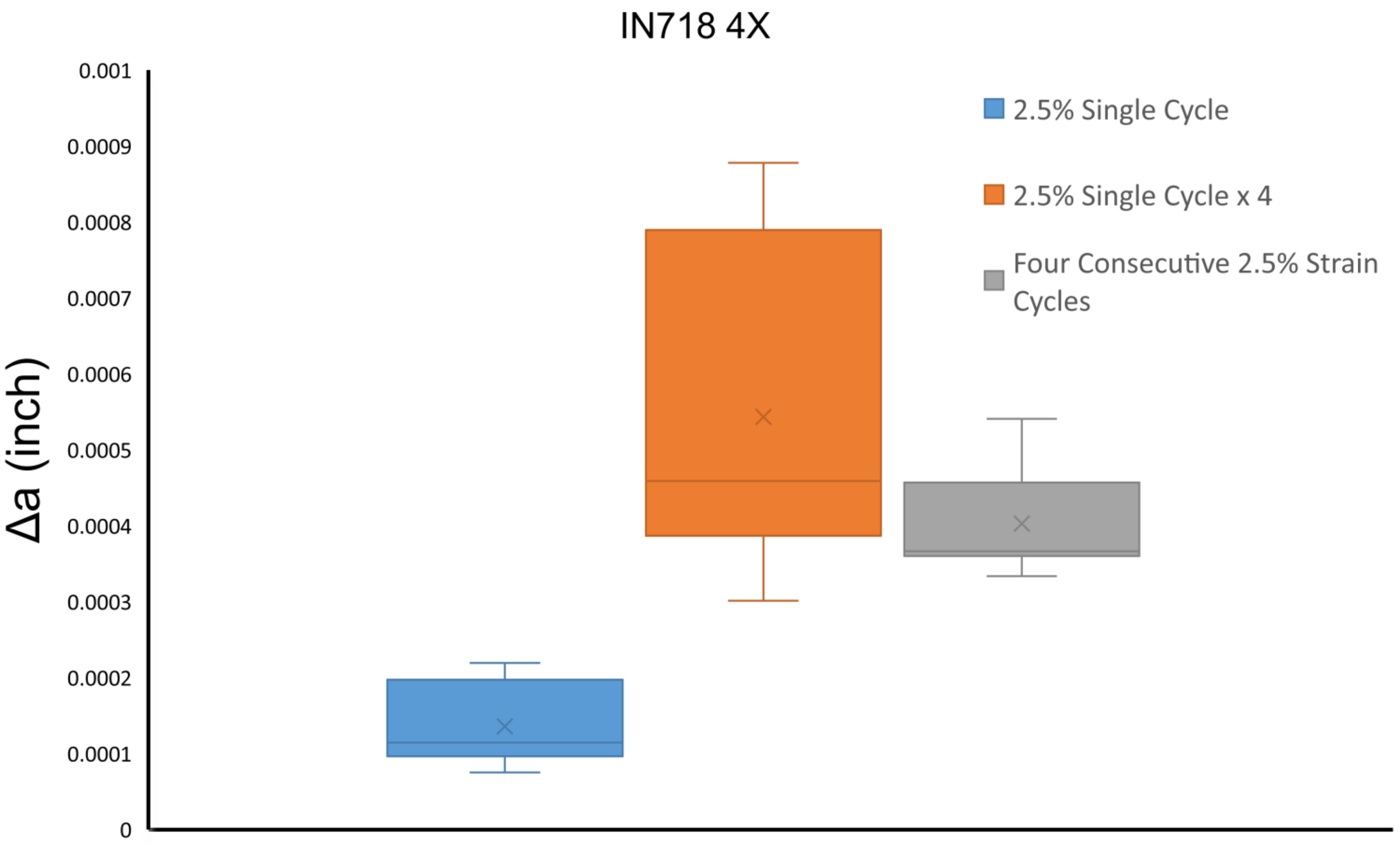
- Crack growth data from 4 autofrettage tests each at a different strain level

- Multiple measurements of crack growth were performed for each test



4 cycle autofrettage crack growth

- Crack growth from 0.05 inch thick In718 specimens compared
- On average the crack growth from the 4 cycle autofrettage is 2.97 times that of the single cycle autofrettage



Findings and Recommendations

- Findings
  - The experimental technique developed was able to measure crack growth during a simulated autofrettage cycle
  - The simulated autofrettage crack growth in IN718 was measured at an average of 0.000086, 0.000136 , and 0.000365 inches, for 1.5%, 2.5% and 3.5% respectively
  - Repeating the autofrettage cycle 4 times caused less crack growth than the crack growth caused by a single cycle multiplied by 4
- Recommendations
  - Recommend that COPV qualification requirements accept using experimental measurements from a single autofrettage test multiplied by 4 to conservatively estimate the crack growth in 4 consecutive autofrettage cycles. This will greatly minimize the experimental requirements for COPV qualification.