Fracture Mechanics Testing of Titanium 6AL-4V in LMP-103S Propellant

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The Need…Range and Mission

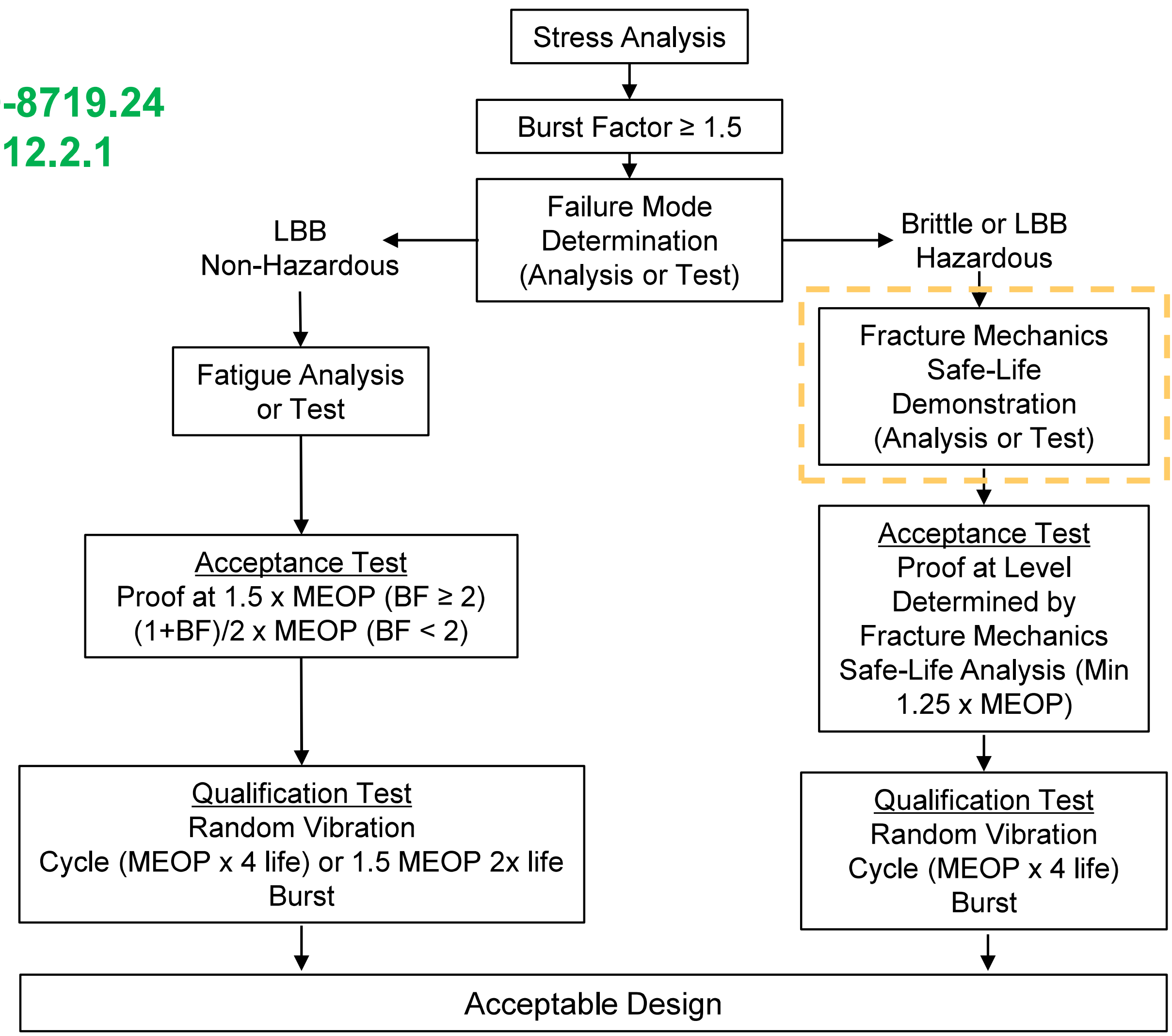
- Safe-Life analysis of titanium alloy Ti 6AL-4V propellant tank is required for flight certification
  - Tank inspected using NDE techniques
    - Fluorescent Penetrant
    - Radiographic
  - Assumed minimum detectable flaw size used in NASGRO fracture analysis software
  - NASGRO analysis material property inputs
    - K_{IC} – Critical stress intensity facture in a Plane-Strain Fracture Toughness (Mode I)
    - K_{EAC} – Environmentally assisted cracking threshold

- Requirement per:
  - AIAA – S-080 Space Systems – Metallic Pressure Vessels, Pressurized Structures, and Pressure Components
  - ASSPCMAN 91-710 V3 – Air Force Space Command Range Safety Manual
  - NASA-STD-8719.24 – NASA ELV Payload Safety Requirements

- Purpose: Investigate the stress intensity threshold for environment-assisted crack growth
  - Ti 6AL-4V bulk forging in combination with LMP-103S propellant
  - Ti 6AL-4V welds in combination with LMP-103S propellant
- Test Method: ASTM E1681, *Standard Test Method for Determining the Threshold Stress Intensity Factor for Environment-Assisted Cracking of Metallic Materials*

Pressure Vessel Design Verification

NASA-STD-8719.24
Section 12.2.1



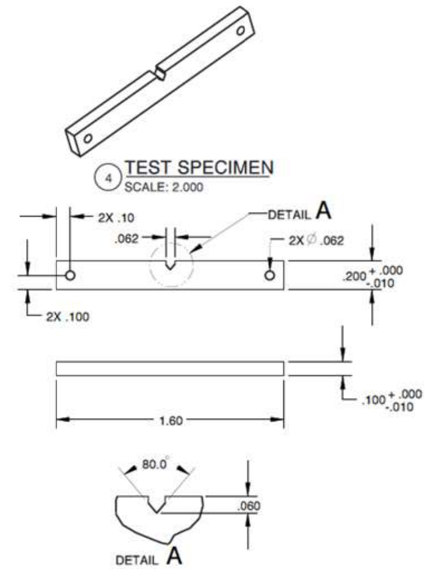
Work Scope

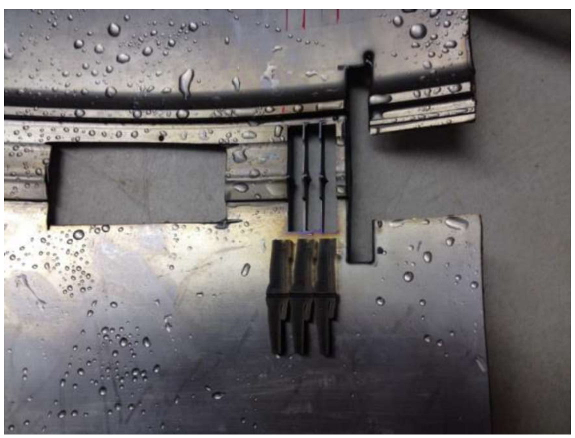
- Fracture Mechanics Testing of Titanium 6Al-4V in LMP-103S
  - Single-edge notched specimens [SE(B)] with fatigue cracks were loaded into test fixtures so that the crack tips were exposed to the propellant
  - Test temperature of 50ºC was worst case design temperature
  - Test duration of 1,000 hours recommended by specification
  - Dead weight loading of specimens in test fluid for soak duration
  - Post-test specimen evaluation including fractography and crack length measurements
- Two test rounds have been completed
  - Mechanically loaded without LMP-103S propellant
    - Stress Intensity targets -- Bulk ~ 25-40 ksi√in / Weld ~ 35-45 ksi√in
  - Mechanically loaded with LMP-103S propellant
    - Stress Intensity targets -- Bulk ~ 22 ksi√in / Weld ~ 31 ksi√in
- Collaboration
  - Northrup Grumman provided tank material and loading guidance
  - GSFC facilitated the LMP-103S exposure testing, test documentation, safety
  - KSC manufactured the coupons, pre-cracked, performed post test analysis, and test fixtures
  - SNSA/ECAPS provided LMP-103S propellant

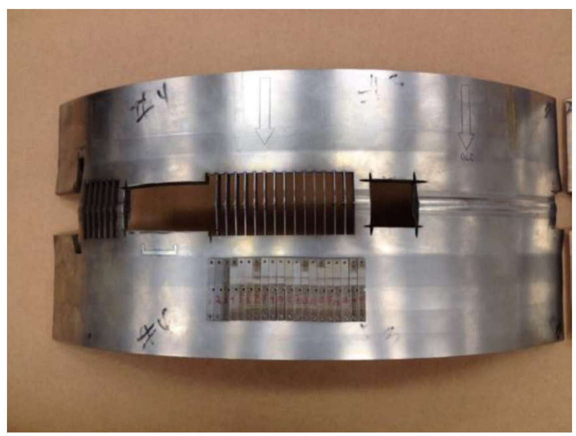
Material and Test Specimen Fabrication

Titanium alloy (Ti 6AL-4V)
Weld Ring

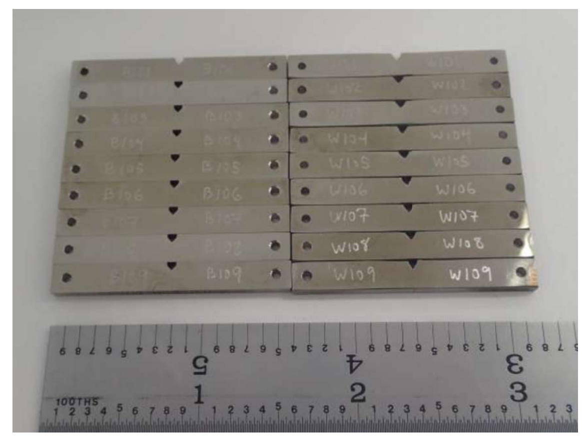
Titanium alloy (Ti 6AL-4V)
Bulk Forging







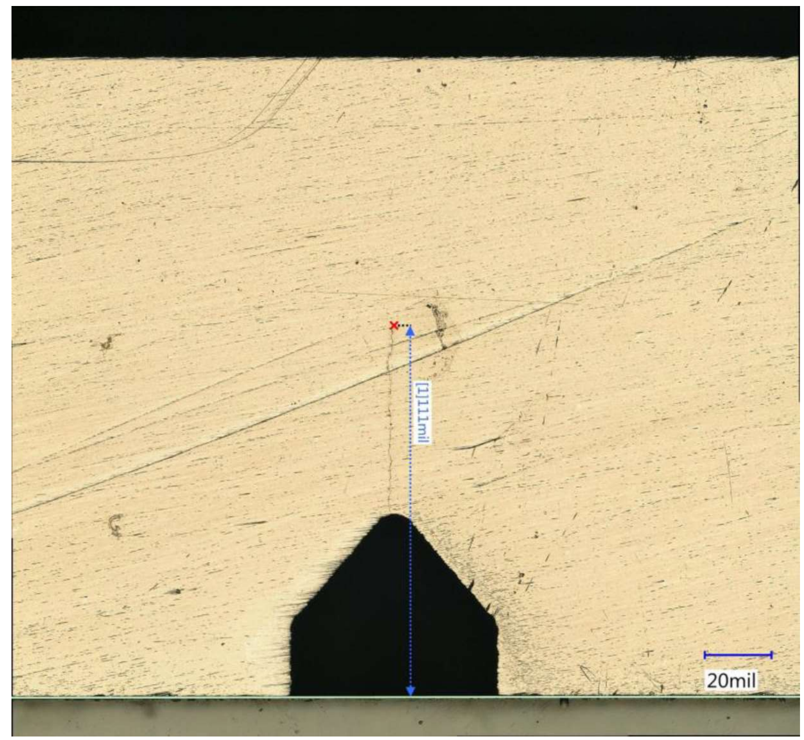
Specimen cut using Wire EDM



LMP-103S Polished Bulk
and Weld Specimens

Specimen Preparation

- Specimen cut using wire EDM
- Ground to remove EDM recast layer
- Polished with diamond paste to 1μm
- Dimensional inspection
- Fatigue pre-crack specimens per ASTM E399 using MTS servo-hydraulic load frame.
  - Crack were grown using a force shedding method
  - Stress intensity was limited to ≤ 15 ksi√in to prevent a plastic deformation at the crack tip
  - Fatigue cracks were grown to 0.10±0.01 inches
  - Crack lengths monitored on the polished sidewalls using digital light microscope
- Passivated, cleaned, and dried per standard procedure
- Post passivation sent back to KSC for inspection
  - Four coupons sent back to KSC for post passivation pre-crack measurement
  - No crack growth – post passivation

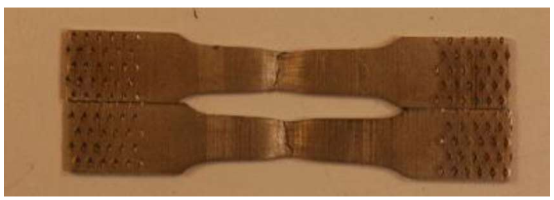


Pre-Crack Length Measurement

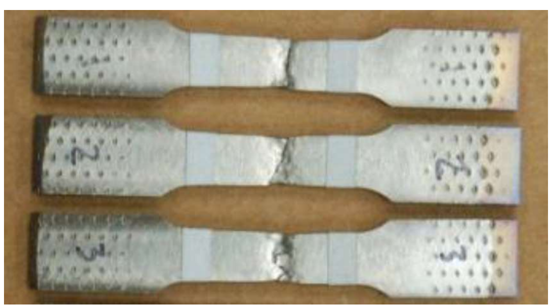
Ti 6AL-4V Material Testing

- Tensile Testing
  - **ASTM E8**
- Yield Strength (σ_{YS}) determined with laser extensometer
- Used in ASTM E399 validity calculations

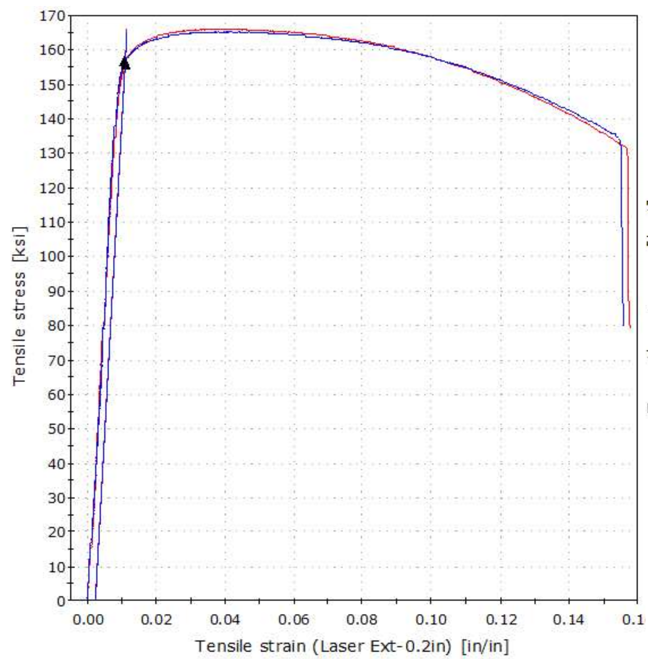
Material	Specimen	Thickness (in)	Width (in)	Gauge Length (in)	Maximum Load (lbf)	Yield Strength-Offset 0.2% (ksi)	Tensile Strength (ksi)	Elongation at Failure (%)
Bulk	B-T1	0.0960	0.2340	0.6504	3727	155.9	165.9	15.7
Bulk	B-T2	0.0960	0.2450	0.6728	3881	156.8	165.0	15.5
Weld	W-T1	0.0860	0.2460	0.6415	3256	139.0	153.9	4.0
Weld	W-T2	0.0845	0.2460	0.6455	3185	140.7	153.2	5.2
Weld	W-T3	0.0850	0.2460	0.6645	3213	141.3	153.7	4.6



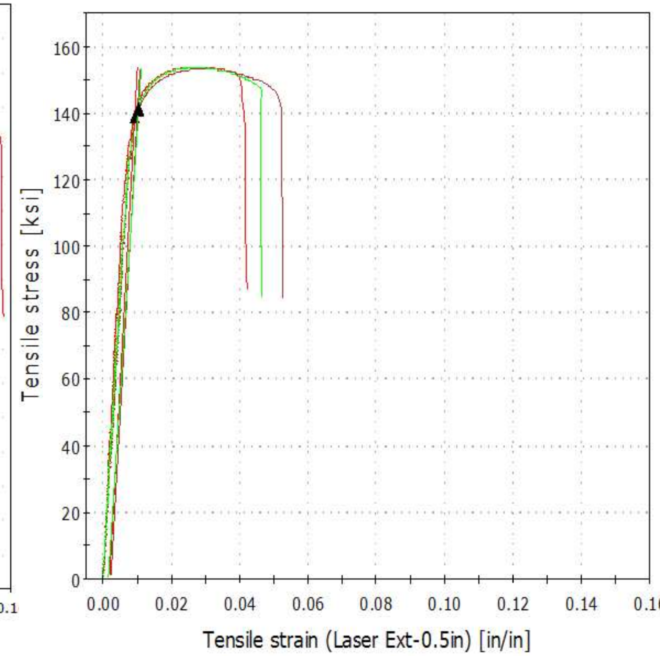
Ti 6AL-4V Bulk Specimens



Ti 6AL-4V Weld Specimens



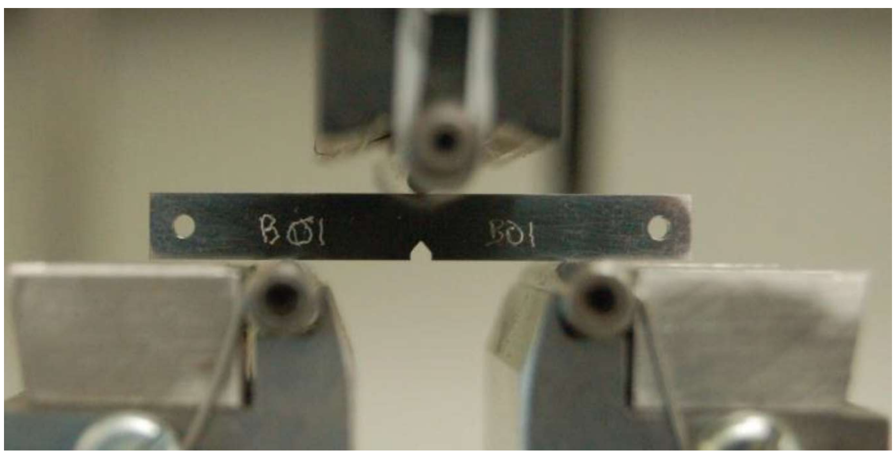
Bulk Stress vs. Strain Curves



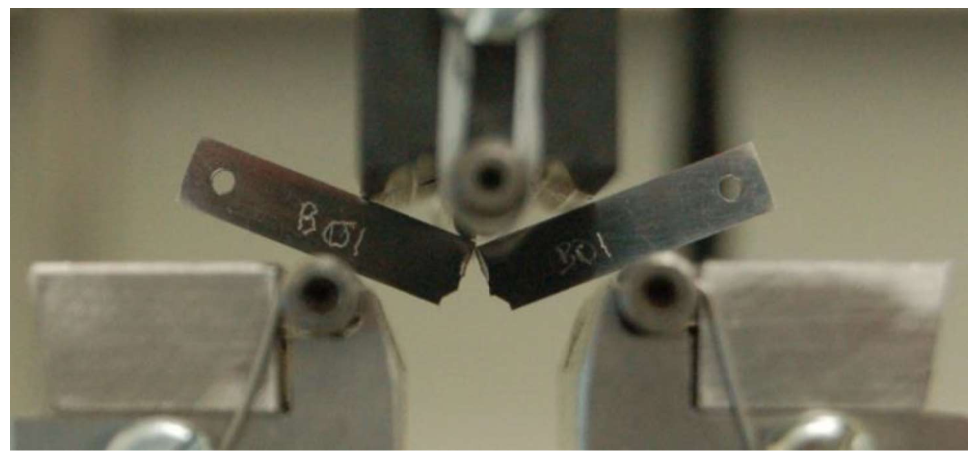
Weld Stress vs. Strain Curves

Ti 6AL-4V Material Testing

- Fracture Toughness
  - Fracture Toughness testing per **ASTM E399-** Standard Test Method for Linear-Elastic Plane-Strain Fracture Toughness K_{IC} of Metallic Materials
    - Fatigue Pre-crack
    - Load to failure
    - Measure initial crack length
    - Validity check of results



SE(B) Specimen Loaded in 3-Point Bending



Failed Fracture Toughness Test Specimen

Ti 6AL-4V Material Testing

$$K = \frac{PS}{BW^{3/2}} * 3\sqrt{\frac{a}{W}} * \frac{1.99 - \left(\frac{a}{W}\right) * \left(1 - \frac{a}{W}\right) * \left[2.15 - 3.93\left(\frac{a}{W}\right) + 2.7\left(\frac{a}{W}\right)^2\right]}{2 * \left(1 + 2 * \frac{a}{W}\right) * \left(1 - \frac{a}{W}\right)^{3/2}}$$

a = crack length
B = specimen thickness
K = stress-intensity factor at the crack-tip in a linear-elastic body
P = force
S = span of three-point bend fixture
W = specimen width

Stress Intensity in 3-point Bending

$$\frac{P_{max}}{P_Q} \leq 1.10$$

Plane Strain Validity Check, Section 9.1.3

$$2.5\left(\frac{K_{EAC}}{\sigma_{YS}}\right)^2 < W - a$$

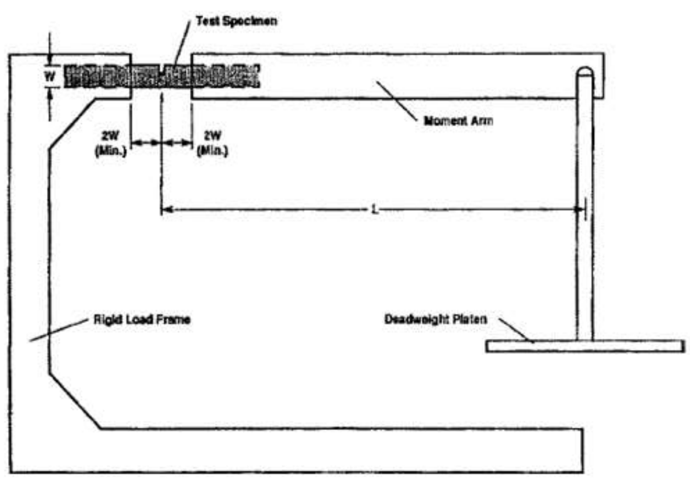
Plane Strain Validity Check, Section 9.1.4

Material	Specimen	Initial Crack Length, a_0 (in)	P_q (lbf)	P_{max} (lbf)	P_{max} / P_q	Fracture Toughness K_Q (ksi√ in)
Bulk	B01	0.1085	143.2	145.8	1.02	45.4*
Bulk	B02	0.1037	154.6	161.7	1.05	45.1*
Bulk	B03	0.0986	166.1	169.5	1.02	44.5*
Weld	W01	0.0890	214.1	268.7	1.26	49.8†
Weld	W02	0.1033	172.2	216.8	1.26	49.5†
Weld	W03	0.0935	212.1	257.7	1.21	50.0†
Weld	W04	0.1023	166.1	208.8	1.26	46.6†

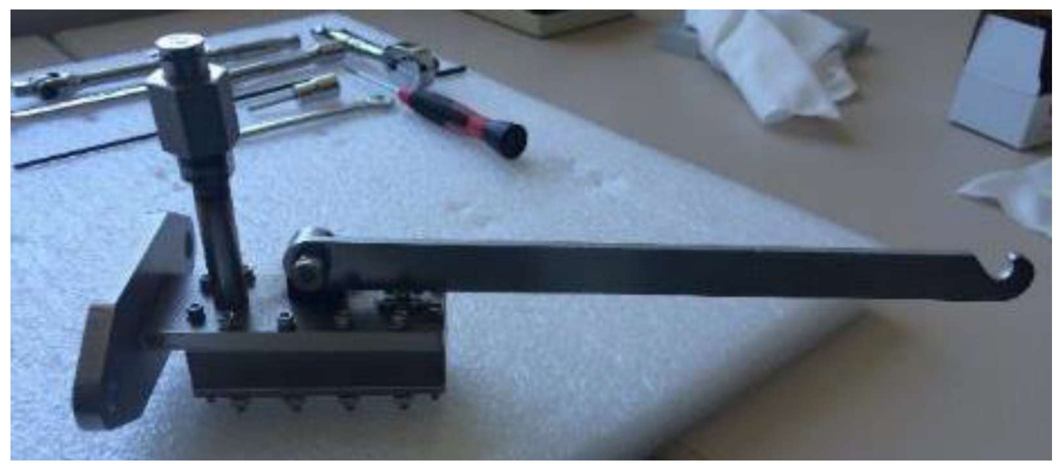
*Invalid according to section 9.1.4 of test method ASTM E399
†Invalid according to sections 9.1.3 and 9.1.4 of test method ASTM E399

Propellant Exposure

- SE(B) were loaded into the fixture in a Class 10,000 cleanroom
- Six (6) Bulk and six (6) weld fixtures were mounted to the stands and leveled
- Each fixture was thine filled with a small volume of LMP-103S propellant
- Fixture stand were then loaded into 100 Liter ovens
- Thermocouples placed on fixture body
- Weights loaded on to the fixture arm mechanically loading the SE(B) crack
- Tested to 1000 hour duration at 50ºC

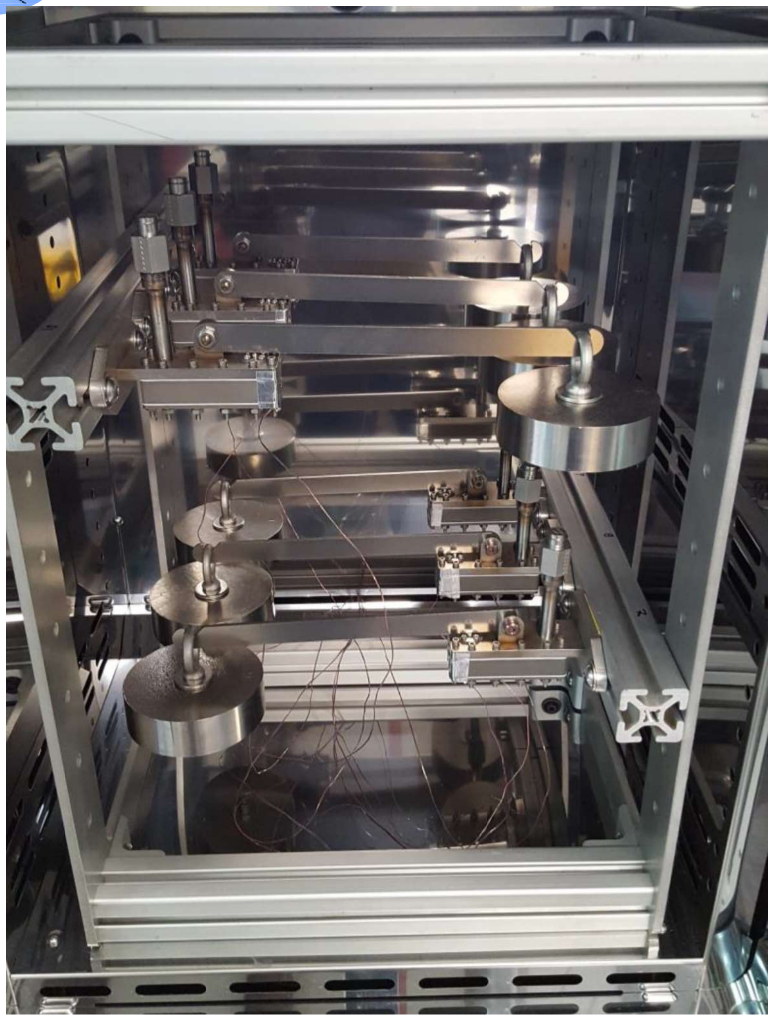


Loading Fixture from ASTM E1681



NASA Designed Loading Fixture for Exposure to LMP-103S Propellant – NASA New Technology Report (1461267027)

Facility and Fixtures



Bulk Tank Fracture and Weld Fixtures Pre-LMP-103 Soak

Post-Exposure Analysis

- After exposure SE(B) specimens which did not visibly fail (all of them) were marked
  - Placed in oven at 300ºC for 30 mins to form high temp oxide marking
  - Post-test fatigued to frame potential crack growth during exposure
- SE(B) specimens were broken open to inspect the crack surfaces for evidence of growth.
- Pre-cracks measured to determine the stress intensity factor, K
- Stress intensity calculated from equation for beam specimen in **ASTM E1681 (below)**
- Stress intensity threshold (K_{EAC})is the highest applied stress intensity that produced neither of the following
  - failure of the specimens during the exposure
  - evidence of crack growth

$$K = \frac{W_a L_a + W_t L}{B W^{3/2}} * \frac{6\left(\frac{a}{W}\right)^{1/2}}{\left(1-\frac{a}{W}\right)^{3/2}} * \left\{1.9878 - 1.3253\left(\frac{a}{W}\right) + \left(1-\frac{a}{W}\right)\left(\frac{a}{W}\right)\left[-3.8308 + 10.1081\left(\frac{a}{W}\right) - 17.9415\left(\frac{a}{W}\right)^2 + 16.8282\left(\frac{a}{W}\right)^3 - 6.2241\left(\frac{a}{W}\right)^4\right]\right\}$$

a	=	*crack length*
B	=	*specimen thickness*
K	=	*stress-intensity factor*
L	=	*length from crack plane to center of gravity of counterweight*
La	=	*length from crack plane to center of gravity of moment arm*
W	=	*specimen width*
Wa	=	*weight of loading arm*
Wt	=	*weight counterweight added to loading arm*

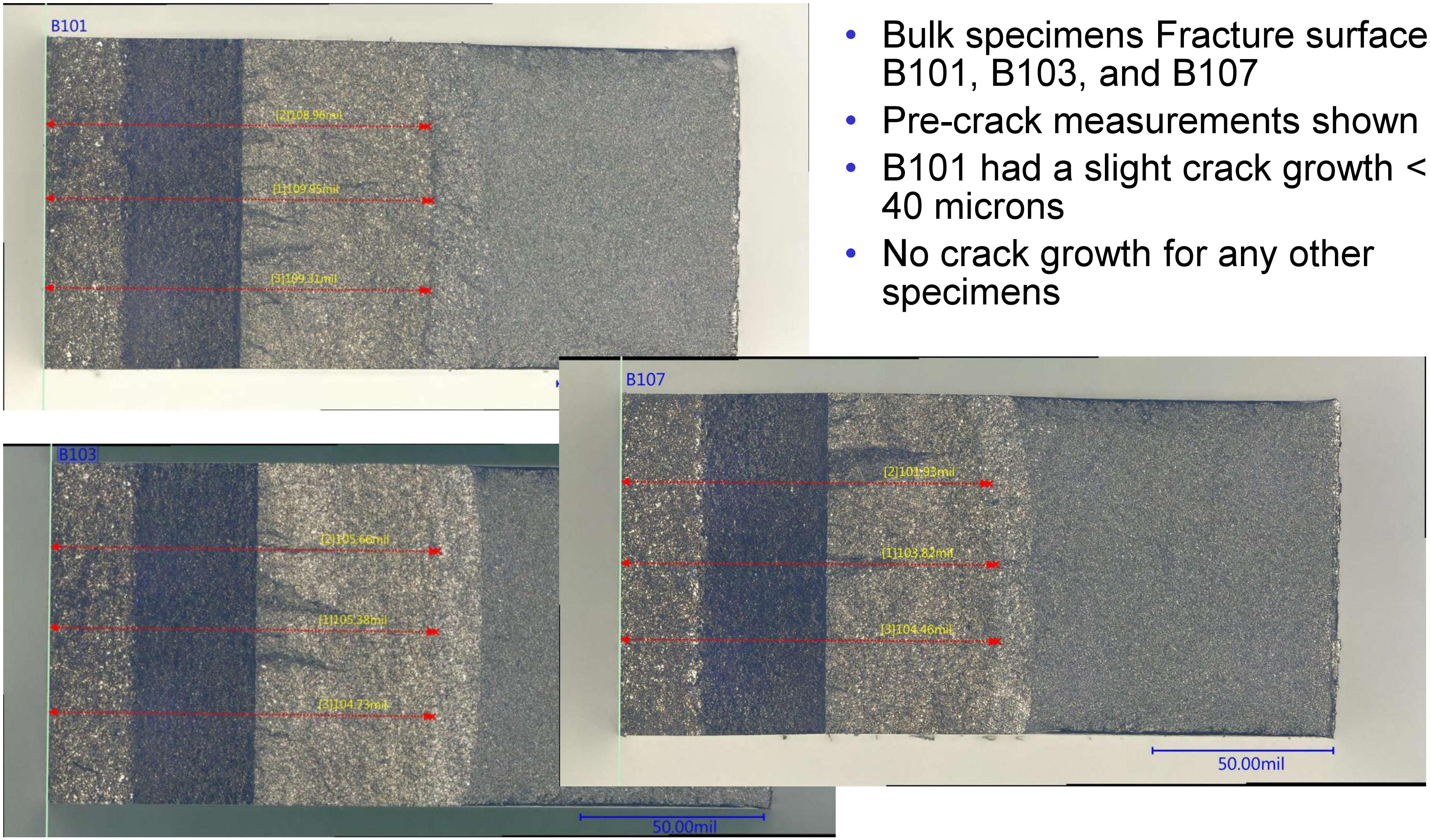
Results – LMP-103S Exposure

Bulk Material

Specimen	Specimen Thickness, B (in)	Specimen Width W, (in)	Initial Crack Length, a_0 (in)	Stress Intensity, K_{EAC} (ksi√in)	Average Stress Intensity, K_{EAC} (ksi√in)	Result	Notes
B101	0.0940	0.1950	0.1094	25.91	25.91	Slight Crack Growth	No failure after 1,000 hours of exposure to LMP-103S monopropellant, but slight (<40 microns) crack growth
B102	0.0935	0.1980	0.1078	24.01	22.5	PASS	No failure or crack growth after 1,000 hours of exposure to LMP-103S monopropellant
B103	0.0925	0.1980	0.1053	23.24		PASS	No failure or crack growth after 1,000 hours of exposure to LMP-103S monopropellant
B105	0.0950	0.1985	0.1008	20.82		PASS	No failure or crack growth after 1,000 hours of exposure to LMP-103S monopropellant
B107	0.0930	0.1980	0.1034	22.47		PASS	No failure or crack growth after 1,000 hours of exposure to LMP-103S monopropellant
B108	0.0940	0.1970	0.1018	21.91		PASS	No failure or crack growth after 1,000 hours of exposure to LMP-103S monopropellant

Fracture Surface – Bulk

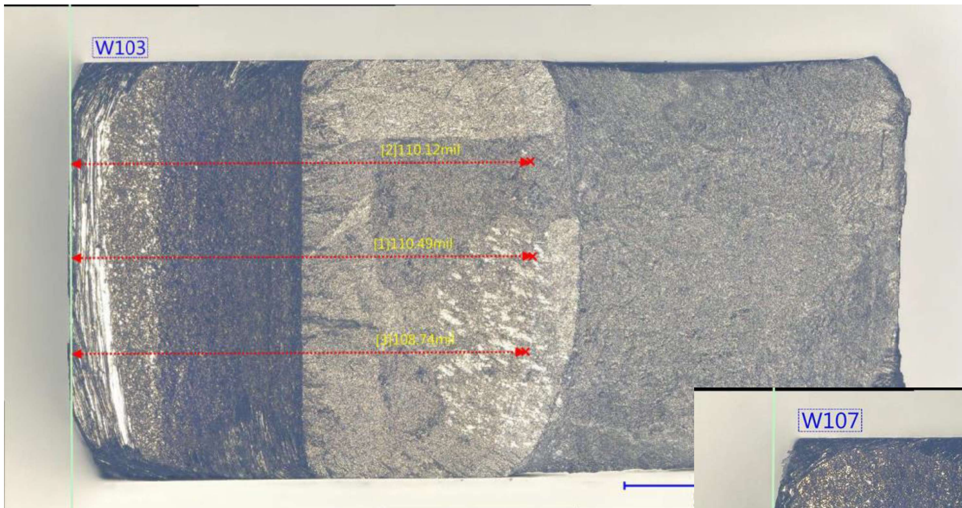
- Bulk specimens Fracture surfaces B101, B103, and B107
- Pre-crack measurements shown
- B101 had a slight crack growth < 40 microns
- No crack growth for any other specimens

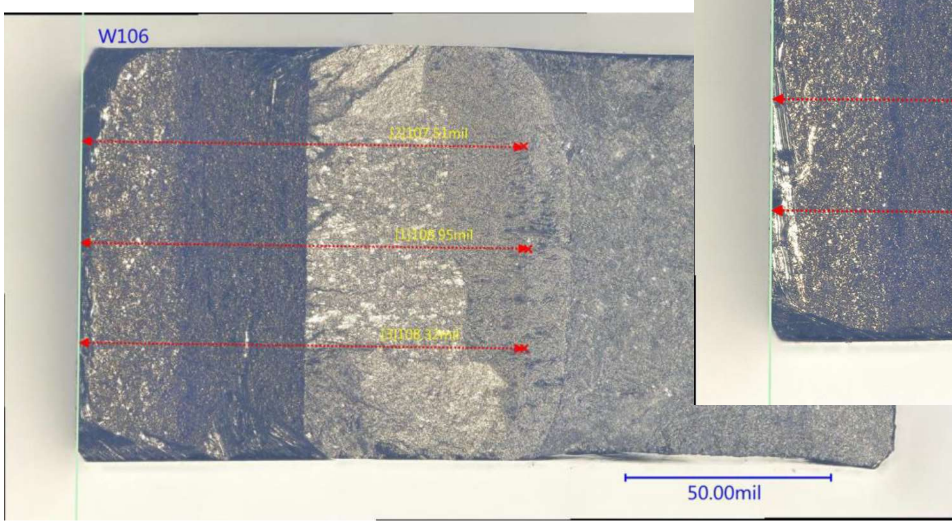


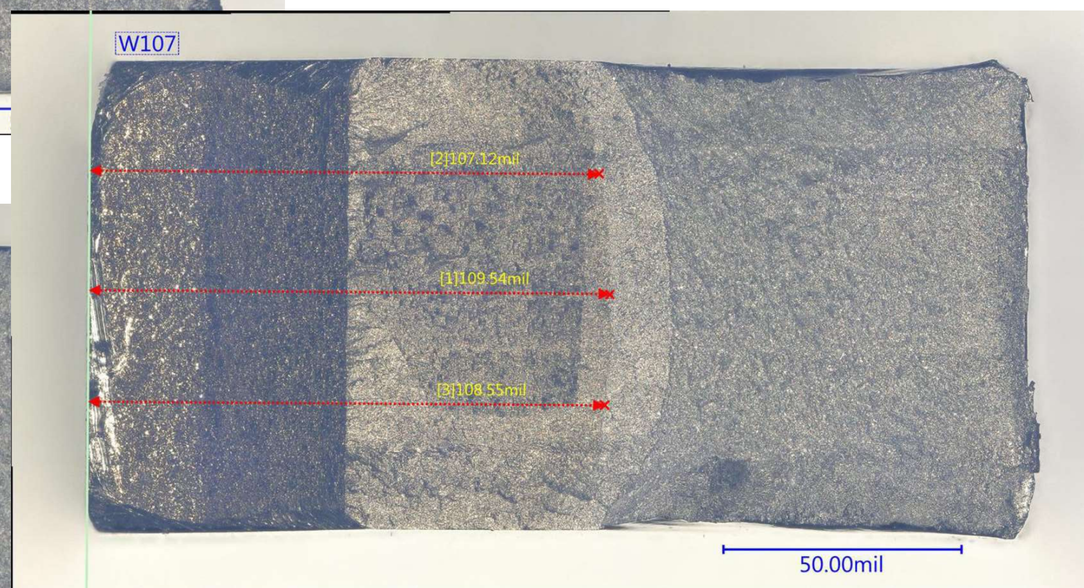
Weld Material

Specimen	Specimen Thickness, B (in)	Specimen Width W, (in)	Initial Crack Length, a_0 (in)	Stress Intensity, K_{EAC} (ksi√in)	Average Stress Intensity, K_{EAC} (ksi√in)	Result	Notes
W101	0.0945	0.1930	0.1043	33.86	36.2	PASS	No failure or crack growth after 1,000 hours of exposure to LMP-103S monopropellant
W102	0.0970	0.1930	0.1099	36.46		PASS	No failure or crack growth after 1,000 hours of exposure to LMP-103S monopropellant
W103	0.0935	0.1935	0.1098	37.45		PASS	No failure or crack growth after 1,000 hours of exposure to LMP-103S monopropellant
W104	0.0920	0.1910	0.1034	35.43		PASS	No failure or crack growth after 1,000 hours of exposure to LMP-103S monopropellant
W106	0.0950	0.1920	0.1083	36.71		PASS	No failure or crack growth after 1,000 hours of exposure to LMP-103S monopropellant
W107	0.0945	0.1920	0.1084	37.06		PASS	No failure or crack growth after 1,000 hours of exposure to LMP-103S monopropellant

Fracture Surface – Weld







- Weld specimens Fracture surfaces W103, W106, and W107
- Pre-crack measurements shown
- No crack growth for any tested weld specimens

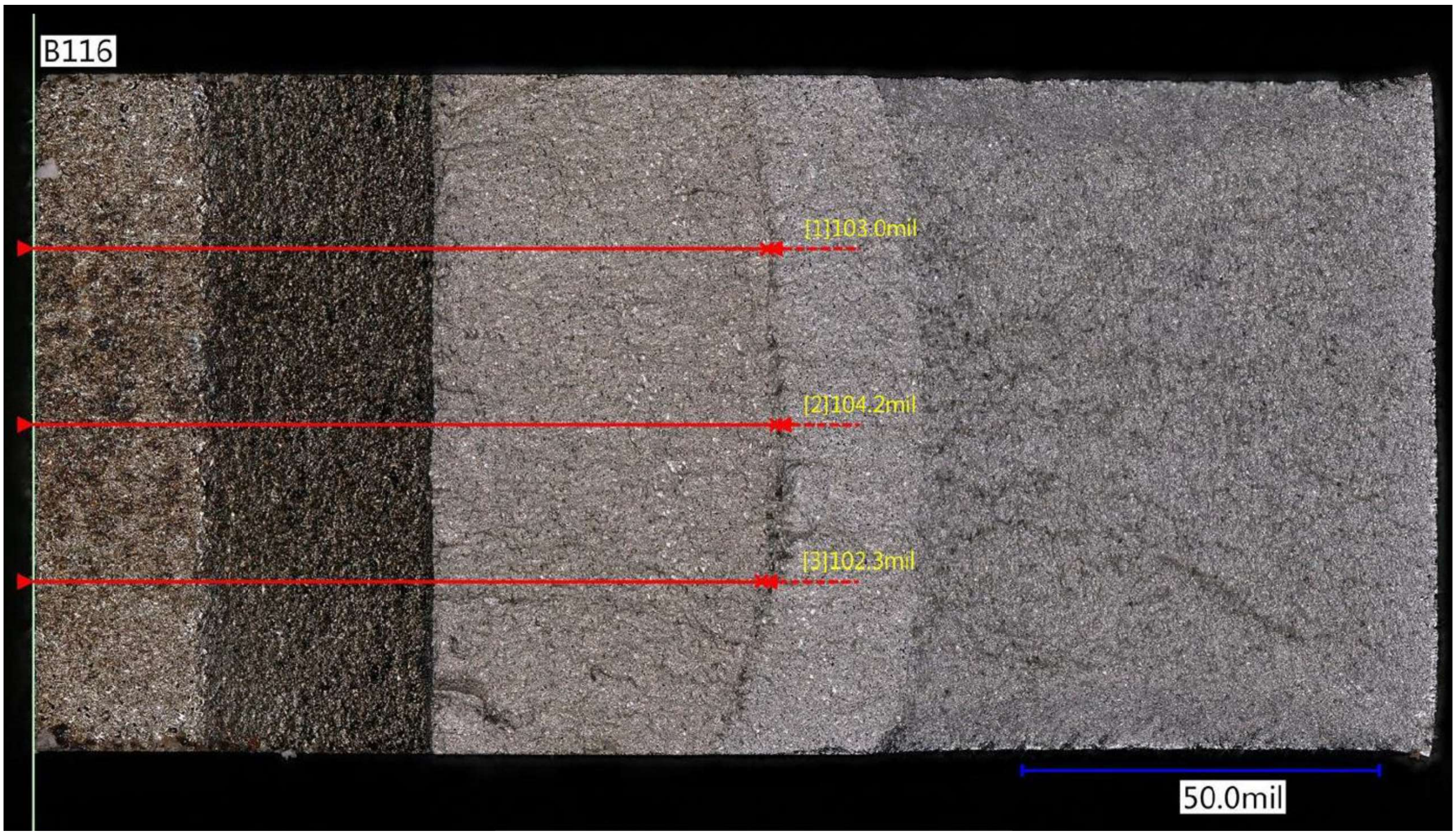
Results – No LMP-103S Exposure

Bulk Material

Specimen	Specimen Thickness, B (in)	Specimen Width W, (in)	Initial Crack Length, a_0 (in)	Stress Intensity, K_{EAC} (ksi√in)	Average Stress Intensity, K_{EAC} (ksi√in)	Result	Notes
B110	0.0949	0.1980	0.0974	23.53	23.9	PASS	Tested without LMP-103S propellant – No Failure or crack growth after 1000 hours
B118	0.0953	0.1980	0.0998	24.27		PASS	Tested without LMP-103S propellant – No Failure or crack growth after 1000 hours
B111	0.0953	0.1966	0.1016	33.99	33.54	PASS	Tested without LMP-103S propellant – No Failure or crack growth after 1000 hours
B119	0.0954	0.1977	0.0997	33.08		PASS	Tested without LMP-103S propellant – No Failure or crack growth after 1000 hours
B112	0.0953	0.1973	0.0968	37.68	37.68	PASS	Tested without LMP-103S propellant – No Failure or crack growth after 1000 hours
B116	0.0959	0.1981	0.1032	41.12	41.12	Slight Crack Growth	Tested without LMP-103S propellant , no failure but slight crack growth

Fracture Surface – B116

- B116 had a slight crack growth



Weld Material

Specimen	Specimen Thickness, B (in)	Specimen Width W, (in)	Initial Crack Length, a_0 (in)	Stress Intensity, K_{EAC} (ksi√in)	Average Stress Intensity, K_{EAC} (ksi√in)	Result	Notes
W110	0.0985	0.1983	0.1026	33.18	34.43	PASS	Tested without LMP-103S propellant – No Failure or crack growth after 1000 hours
W118	0.0978	0.1971	0.1054	35.67		PASS	Tested without LMP-103S propellant – No Failure or crack growth after 1000 hours
W112	0.0986	0.1975	0.1016	40.02	41.97	PASS	Tested without LMP-103S propellant – No Failure or crack growth after 1000 hours
W121	0.0964	0.1988	0.1072	43.91		PASS	Tested without LMP-103S propellant – No Failure or crack growth after 1000 hours
W111	0.0971	0.1974	0.1086	44.85	44.4	PASS	Tested without LMP-103S propellant – No Failure or crack growth after 1000 hours
W114	0.0937	0.1974	0.1039	43.95		PASS	Tested without LMP-103S propellant – No Failure or crack growth after 1000 hours

Damage Tolerance

- A damage tolerance, or crack growth assessment, is performed as part of the structural analysis verification process by means of NASGRO
- Crack growth propagation is performed with the knowledge of:
  - Tank geometry (wall thickness, and diameter)
  - Initial crack size (determined through NDE inspection limitation)
  - Associated number of fully reversed cycles at a know stress state
  - Crack growth material properties (e.g., surface effective….)”
- NASGRO calculates a stress intensity factor at the crack tip given geometry and state of stress
  - If the crack propagates through the section and the remaining material cannot support the net stress, or the crack tip stress intensity factor is greater than the surface effective fracture toughness, the part is predicted to fail
  - Requirement is 4x propellant tank service life
- Assessment locations:
  - Dome area – parent Ti 6Al-4V material
  - Weld girth ring – weld Ti 6Al-4V material
- Typical assessment performed using K_{IE}, effective fracture toughness ignoring the environmental effects from K_{EAC}
- A subsequent set of runs activated the K_{EAC} based on bulk and weld material fracture mechanic testing in LMP-103S

Fracture Spectra Service Life

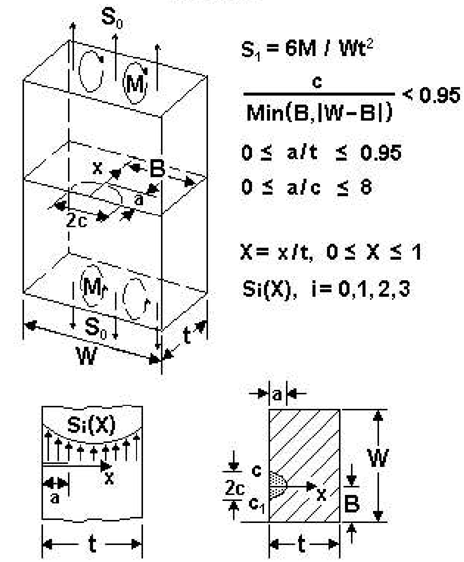
- A fracture spectra service life table (stress vs. number of cycles) was developed
- Accounts for all mission phases: proof and acceptance, ground testing, etc

Phase	NASGRO Step	Cycles	Steady State		Dynamic Loads		Dome – So		Weld – So	
			Pi (psig)	Pf (psig)	Lateral (G)	Axial (G)	t_1	t_2	t_1	t_2
Tank Level Acceptance – Vendor Level	1	1	0	450	0.0	0.0	0.000	0.986	0.000	1.000
	2	2	0	360	0.0	0.0	0.000	0.789	0.000	0.800
Harness Checkouts	3	1	0	30	0.0	0.0	0.000	0.066	0.000	0.067
Propulsion Subsystem – Proof	4	2	0	450	0.0	0.0	0.000	0.986	0.000	1.000
Propulsion Subsystem – MEOP	5	4	0	360	0.0	0.0	0.000	0.789	0.000	0.800
Observatory Thermal Vacuum	6	1	0	30	0.0	0.0	0.000	0.066	0.000	0.067
Transportation 7: Transportation – 3 days road 8: X-direction mechanical loading 9: Y-direction mechanical loading 10: Z-direction mechanical loading	7	1	0	30	0.0	0.0	0.000	0.066	0.000	0.067
	8	10M	29.8	30.3	1.0	0.0	0.080	0.081	0.070	0.071
	9	10M	29.8	30.3	1.0	0.0	0.080	0.081	0.070	0.071
	10	10M	29.8	30.3	0.0	2.5	0.073	0.074	0.071	0.072
Flight Pressurization and Launch 11: Flight Pressurization 12: X-direction mechanical loading 13: Y-direction mechanical loading 14: Z-direction mechanical loading	11	1	0	360	0.0	0.0	0.000	0.789	0.000	0.800
	12	1000	359.8	360.3	14.7	0.0	0.999	1.000	0.859	0.860
	13	1000	359.8	360.3	14.7	0.0	0.999	1.000	0.859	0.860
	14	1000	359.8	360.3	0.0	14.7	0.834	0.835	0.829	0.830
On – Orbit	15	1	360	0.0	0.0	0.0	0.789	0.000	0.800	0.000

NASGRO Results

- Multiples NASGRO runs were performed
- The initial crack sizes (a_i) and aspect ratios (a/c) were determined by established NDE techniques.
- For the dome area, dye-penetrant inspection is used to locate cracks while radiographic (i.e., x-ray) techniques are more appropriate for girth-ring welded areas.
- All cases including KEAC show passing results for the 4x life
  - For the dome area , the value calculated at the crack almost exceeded the set K_{EAC} value, which showed environmental effects can reduce service life for an existing design
- Thickness reduction also investigated to assess failure sensitivity

SC30



NASGRO SC30 Crack Case

Case	Location	Thickness (t) - inches	NDE	a_i (inches)	a/c	a_f (inches)	C_f (inches)	K_{max} (ksi√in)	K_{IE} (ksi√in)	K_{EAC} (ksi√in)	$a_f < t$	$K_{max} < K_{IE}$ $K_{max} < K_{EAC}$
No Use of K_{EAC}	Tank Dome	0.057	Dye-Penetrant	0.012	0.20	0.0123	0.0600	21.0	50.0	---	PASS	PASS
				0.025	1.00	0.0252	0.0253	21.9	50.0	---	PASS	PASS
	Girth Weld	0.212	Radiography	0.1484	1.00	0.1489	0.1493	34.1	50.0	---	PASS	PASS
Including K_{EAC}	Tank Dome	0.057	Dye-Penetrant	0.012	0.20	0.0123	0.0600	21.0	50.0	22.5	PASS	PASS
				0.025	1.00	0.0252	0.0253	21.9	50.0	22.5	PASS	PASS
	Girth Weld	0.212	Radiography	0.1484	1.00	0.1489	0.1493	34.1	50.0	36.2	PASS	PASS
Material Thickness Reduction, Including K_{EAC}	Tank Dome	0.053	Dye-Penetrant	0.012	0.20	0.0121	0.0600	22.7	50.0	22.5	PASS	FAIL
		0.054		0.025	1.00	0.0250	0.0250	22.8	50.0	22.5	PASS	FAIL
	Girth Weld	0.186	Radiography	0.1302	1.00	0.1302	0.1302	36.3	50.0	36.2	PASS	FAIL

Conclusions

- The threshold stress intensity factor for environment-assisted cracking of Ti6Al-4V bulk forging material and weld material when exposed to LMP-103S propellant was determined
- K_{EAC} for the bulk tank material at least 22.5 ksi√in
- K_{EAC} for the weld material was at least 36.2 ksi√in
- B101 specimen showed slight crack growth at 25.9 ksi√in
  - Removed from average of Bulk specimens
- To evaluate the adapted ASTM 1681 fixture design, a dry test was performed to investigate the crack grown without exposure to the LMP-103S propellant to further assess the un-wetted stress intensity factor
  - Bulk material stress intensity threshold at ~40 ksi√in
  - Weld material stress intensity threshold at ~42 ksi√in
- A generic tank was evaluated for a basic damage tolerance assessment
  - This is a simplistic case to illustrate the process; however, a rigorous structural analysisis is required for spaceflight propellant tank safe-life demonstration to meet Range requirements
- Future work is recommended to conduct further rounds of testing
  - Build statistics

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