FRACTURE MECHANICS TESTING OF TITANIUM 6AL-4V IN LMP-103S PROPELLANT

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ABSTRACT:

Propellant tank safe-life analysis is a spacecraft propulsion subsystem Launch Range processing requirement. The material property inputs for the safe-life analysis include the stress intensity factor for environment-assisted cracking (K_{EAC}). The K_{EAC} for titanium alloy Ti 6Al-4V in LMP-103S propellant was determined experimentally using an innovative test method following ASTM E1681, Standard Test Method for Determining Threshold Stress Intensity Factor for Environment-Assisted Cracking of Metallic Materials. This effort was a collaboration between NASA Goddard Space Flight Center and NASA Kennedy Space Center to expose the test specimens in the propellant, while loaded in the test fixtures, for 1000- hour (42 days) at 50°C.

Two test rounds have been completed to date; 1) testing mechanically loaded specimens but without propellant and 2) testing mechanically loaded specimens wetted with LMP-103S propellant. The dry test was to evaluate the crack growth without exposure to the LMP-103S propellant, and further assess the un-wetted stress intensity factor for the full 1000-hour duration. The second round of testing included the propellant soak for the requisite 1000- hour at 50°C. Current results show that the threshold intensity factor for environment-assisted cracking (exposed to LMP-103S) is 22.5 ksi√in for the bulk material and 36. 2 ksi√in for the weld material.

A generic 'candidate' tank geometry and material thickness is developed for a damage tolerance of known surface cracks below the nondestructive inspection technique detection limit. Evaluations with and without the use of a threshold intensity factor for environment-assisted cracking is performed for the required 4x propellant tank service life using the software tool NASGRO.

NOMENCLATURE

a	= *crack length*
a_0	= *initial crack length*
B	= *specimen thickness*
EDM	= electrical discharge machine
GSFC	= *Goddard Space Flight Center*
J_{Ic}	= *elastic-plastic fracture toughness*
K	= *stress-intensity factor at the crack-tip in a linear-elastic body,* ksi√in
K_I	= *mode I stress intensity factor in a plane-strain loading condition*
K_{IC}	= *critical stress intensity factor in a plane-strain loading condition*
K_{IE}	= *effective fracture toughness*
K_{EAC}	= *stress intensity factor threshold for environmentally assisted crack growth*
K_{IEAC}	= *stress intensity factor threshold for plane strain environmentally assisted crack growth*
KSC	= *Kennedy Space Center*
K_Q	= *critical stress intensity factor not meeting the plane-strain loading criteria*
L	= *length from crack plane to center of gravity of counterweight*
L_a	= *length from crack plane to center of gravity of moment arm*
L-S	= *crack propagation through the material thickness and normal to the direction of principle deformation*
M	= *moment,* $L*W_t+L_a*W_a$
MEOP	= *Maximum Expected Operating Pressure*
NDE	= *nondestructive evaluation*
P	= *force*
R	= *stress ratio, as ratio of the maximum stress to minimum stress during cyclic fatigue σ*
STA	= *solution treated and aged*
S	= *span of three point bend fixture*
SE(B)	= *single-edge notched specimen loaded in bending*
W	= *specimen width*
W_a	= *weight of loading arm*
W_t	= *weight of counterweight added to loading arm*

1. INTRODUCTION

Fracture mechanics safe-life (or damage tolerance) demonstration is mandatory for propellant flight tank certification at U.S. Launch Ranges. This is defined in Range safety requirement documents, ASSPCMAN 91-710 and NASA-STD-8719.24, and further AIAA Standard S-080, which is the industry standard for metallic pressure vessels. The fracture mechanics safe-life analysis validates the pressurized propellant tank design for the expected service life. Propellant tanks are fracture critical life limited pressure vessels and flight qualified to a cumulative number maximum expected operating pressure (MEOP) and proof pressure cycles. For a propellant tank to remain in the qualified operational envelop, this total pressure cycle count must remain within the propellant tank acceptance testing, the propulsion system integration and test phases, and on-orbit life.

During the propellant tank manufacturing, the tank material is inspected using fluorescent penetrant, and radiographic nondestructive evaluation (NDE) techniques. These inspections screen the material for surface flaws and cracks above the technique's detection limit. This determines the maximum size for an undetected flaw on the material surface. The safe-life analysis then models a propellant tank with this maximum crack size (the undetected flaw) to demonstrate that it will not fail when subjected to a specific number of pressure cycles. Assuming a surface flaw is present on the tank material surface, a damage tolerance assessment confirms that any crack large enough to cause failure would have been identified in inspection. A key input for this damage tolerance analysis includes the stress intensity factor for environment-assisted crack growth (K_{EAC}) when exposed to the propellant.

Titanium alloy Ti 6Al-4V is an optimal propellant tank and pressure vessel material, exhibiting high-strength-to-weight and corrosion resistance. Historically, Ti 6Al-4V material structural integrity has been tested for flaw propagation under sustained loading while exposed hydrazine [1]. These tests on Ti 6AL-4V material determined the K_{EAC} in combination with this propellant. The experimental findings provided fundamental design rationale for pressurized propellant tank material in use with hydrazine propellant applications. Foundational testing is requisite to establish the K_{EAC} of the Ti 6AL-4V material under sustained loading while exposed to any new propellant.

The testing documented herein investigates the K_{EAC} of Ti 6Al-4V in combination with LMP-103S propellant. This testing is performed to establish the central input for propellant tank fracture mechanics damage tolerance analysis. This work was a collaboration with NASA's Godard Space Flight Center (GSFC) and Kennedy Space Center (KSC). KSC was responsible for the load fixture design and build, specimen manufacture and preparation, and post-test crack analysis. GSFC was responsible for preparing the test facility to handle LMP-103S propellant, the test fixtures assembly procedure, propellant handling procedure to transfer LMP-103S propellant into the test fixture, exposure of the loaded specimens to the propellant at elevated temperature, and post-test fixture decontamination.

Northrop Grumman, formerly ATK PSI, provided NASA a titanium forging and propellant tank qualification girth weld ring. Northrop Grumman delivers numerous propellant tanks to NASA and propulsion subsystem commercial suppliers, thus testing this Ti 6Al-4V tank material delivers confidence for flight applications. The LMP-103S propellant was contributed through the NASA and Swedish National Space Agency Implementing Arrangement [2].

Propellant tanks are typically fabricated by welding two hemispherical forgings. Because of this, this testing includes bulk forging and weld material specimens. Testing was performed according to ASTM E1681, Standard Test Method for Determining Threshold Intensity Factor for Environment-Assisted Cracking of Metallic Materials [3]. This testing additionally built upon the successful methods documented in 2015 [4].

Using the experimentally determined bulk and weld Ti 6Al-4V material K_{EAC}, a candidate tank design is evaluated for damage tolerance using NASGRO [5] fracture analysis software. Historically, NASGRO fracture assessments for Ti 6Al-4V and hydrazine combinations have been conducted using the K_{EAC} established thorough 24-hour duration sustained load testing on uniaxially loaded fracture mechanics specimens containing part-through cracks [1].

2. PROCEDURE

In accordance with ASTM E1681, the stress intensity threshold values for environmentally assisted cracking of Ti 6Al-4V forging and weldment material was measured in LMP-103S propellant. Fatigue pre-cracked single-edge bend specimens, annotated as SE(B), were loaded into test fixtures enabling the crack tips to be continuously wetted with the propellant for 1,000-hour (42 day) duration. The test was performed at a 50°C temperature, which was chosen based on the highest expected temperature a flight tank would experience throughout service life and further the worst case for corrosive effects of the propellant. The duration of the test was in accordance with the material recommendations in ASTM E1681.

Upon completion of the exposure, SE(B) specimens that did not fail were marked with post-test fatigue cracks. Specimens were then opened to inspect the crack surfaces for evidence of growth during propellant exposure. The threshold stress intensity value, K_{EAC}, is the highest force-bracketed stress intensity that did not cause crack growth.

2.1. SPECIMEN PREPERATION

The test material shown in Figure 1 below included a Ti 6Al-4V tank forging and a qualification girth weld ring. The tank forging was in a solution treated and aged (STA) condition to represent the bulk tank membrane. The girth weld ring was unaged representing the Ti 6Al-4V propellant tank flight weld. SE(B) specimens were machined to the dimensions shown in Figure 2. Bulk tank specimens were cut from the forging so that cracks would grow in the L-S direction, which corresponds to crack propagation from hoop stress in a pressurized tank. Weld specimens were cut from the weld ring with the crack in the through-thickness plane and growing parallel to the weld solidification direction. Specimens were fabricated with a wire electrical discharge machine (EDM). Each SE(B) specimen surface was ground to remove the recast layer and polished to enable view of the cracks on the sidewall of the specimen.

2.2. TENSILE AND METALOGRAPHY

It was necessary to determine the tensile properties, specifically the yield strength, of the bulk and weld Ti 6Al-4V material in order to calculate the validity of the fracture toughness and threshold stress intensity results. Tensile properties were determined referencing ASTM E8 [6] for both the bulk and the weld material. Sub-size tensile specimens were cut using the wire EDM. The gauge length was reduced from 1.0 inches to 0.75 inches because of the size of the sections available for testing. Bulk specimens were tested in the wrought direction and weld specimens were tested perpendicular to the direction of the weld solidification.

2.3. FATIGUE PRE-CRACKING

Fatigue pre-cracks were induced on the notched SE(B) specimens using a servo-hydraulic load frame. A three-point bending test fixture (Figure 3)

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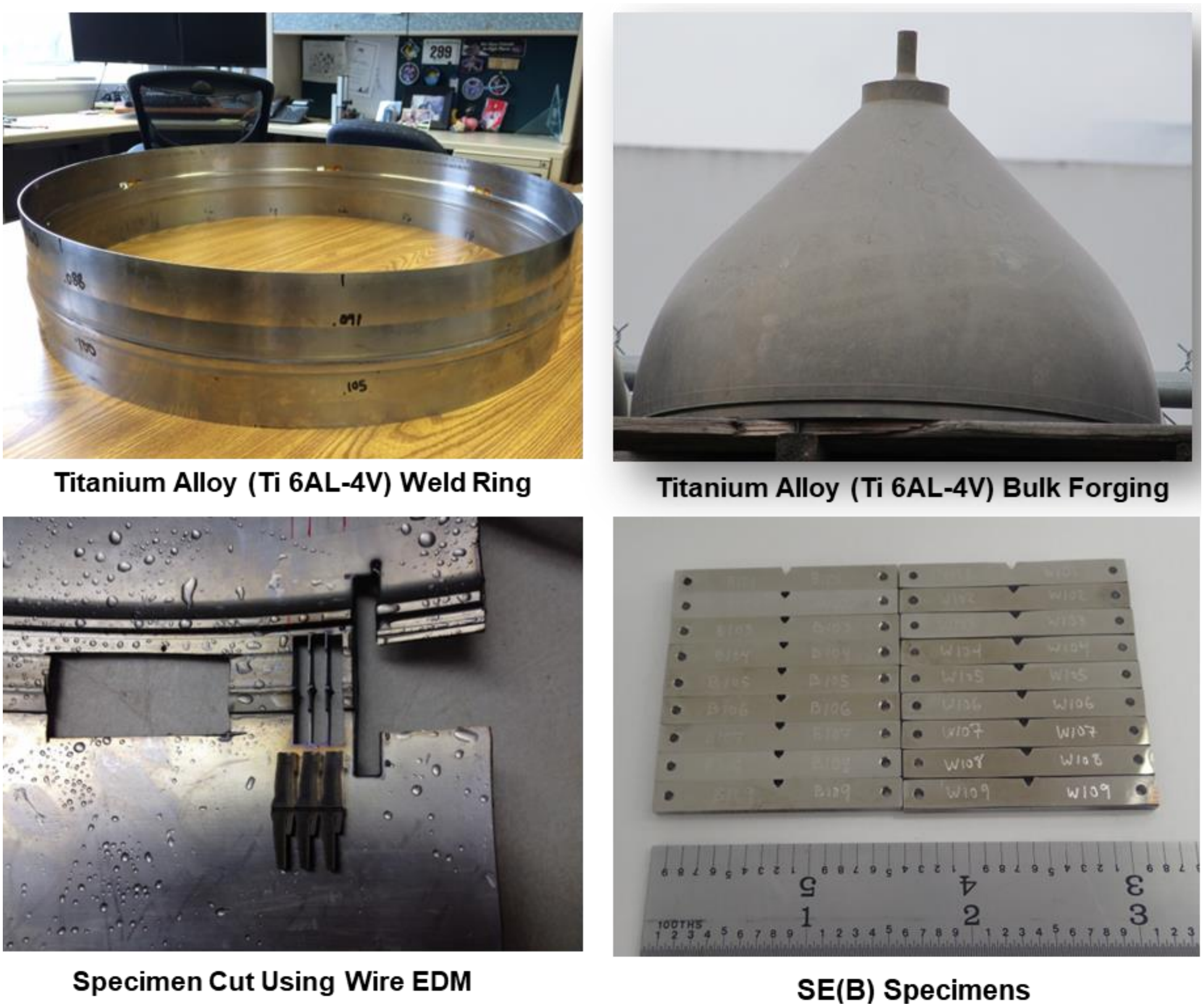


Figure 1. Titanium 6AL-4V Material

was configured referencing ASTM E399 [7] Annex 2 with a load span of 0.8 inch. Cracks were grown using a force shedding method with stress ratio, R, of 0.1. Depending on the fatigue crack length, the maximum load in each cycle started at 110 lbf and was reduced to, 90, 70, 60, 50 and 40 lbf as the crack propagated. Using Eq. (1), the stress intensity was never above 15 ksi√in to prevent plastic deformation at the crack tip. The fatigue crack length was monitored on the sidewalls of the specimen (Figure 3), using a digital light stereomicroscope. The target length for the fatigue cracks was 0.10±0.01 inch. Specimens were cleaned prior to loading in the test fixtures per ASTM G1 [8].

2.4. FRACTURE TOUGHNESS

Fracture toughness testing was performed on specimens for both bulk tank and the weld material in accordance with ASTM E399 [7]. Results were used to design and build test fixtures and weights for the threshold stress intensity testing that followed.

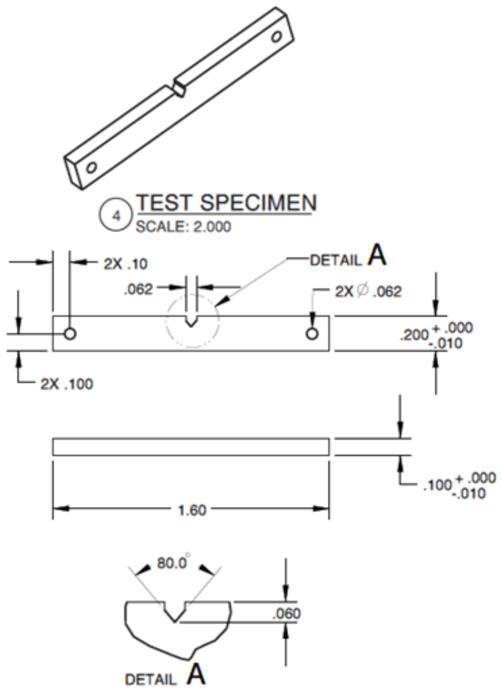
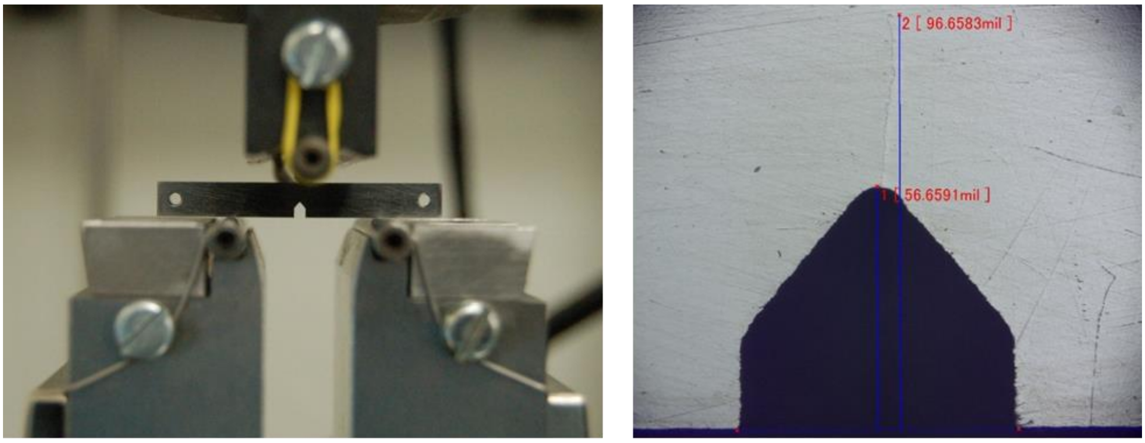


Figure 2. SE(B) Drawing, dimensions are in inches

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



Three-Point Bend Fixture **Fatigue Crack Growth Monitoring**

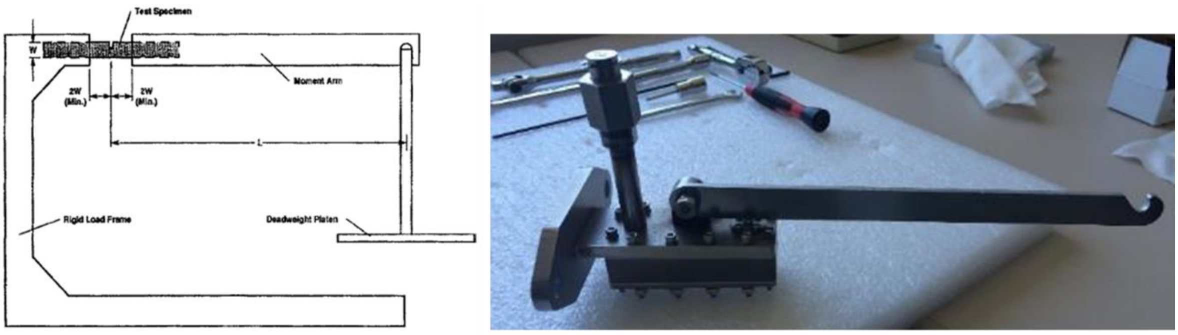
Figure 3. SE(B) specimens Pre-Cracking [4]

3. PROPELLANT EXPOSURE

NASA designed test fixtures for SE(B) specimens, which incorporated a cantilever bending device similar to the ASTM 1681 fixture depicted in Figure 4 [8]. The NASA adapted test fixture shown in Figure 4 kept one end of the SE(B) test specimen fixed while keeping the crack under sustained loading. The crack tip was continuously wetted with LMP-103S propellant throughout the 1000- hour (42 day) test duration. The fixture design contained the SE(B) test specimen inside a sealed volume and incorporated a fill and drain propellant port to allow for the test specimen installation before exposing to the test propellant.

Twelve individual SE(B) sample fixtures and two fixture stands were manufactured, each capable of holding six test fixtures, as illustrated in Figure 5. Six (6) bulk specimens were tested in one stand and six (6) weld specimens in another stand.

The SE(B) specimens and fixtures were passivated and cleaned for LMP-103S propellant exposure. To ensure that the SE(B) fatigue crack was unchanged due to this passivation and cleaning procedure, two bulk and two weld test specimens were inspected post passivation and cleaning, using a digital light stereomicroscope. The four (4) SE(B) specimens indicated no sign of crack growth based on this preparatory procedure.



Loading Fixture from ASTM E1681 **NASA Designed Loading Fixture for Exposure to LMP-103S Propellant – NASA New Technology Report (1461267027)**

Figure 4. SE(B) specimens Pre-Cracking

Figure 5. SE(B) Bulk Specimens Under Test

The SE(B) specimens were loaded into the fixture in a Class 10,000 cleanroom. Following this, six (6) bulk fixtures and six (6) weld fixtures were mounted to the stands and leveled. Each fixture was then filled with a small volume of LMP-103S propellant. These stands were then loaded into the two (2) 100 Liter ovens. Thermocouples were placed on the body of the SE (B) loading fixture to collect temperature measurements throughout the test. The final step was placing the weights onto the fixture arm loading the SE(B) crack. Figure 5 illustrates the bulk specimen stand in the oven just prior to the start of testing.

A facility at NASA GSFC was repurposed for this testing and the required LMP-103S propellant handling. The 1000-hour (42 day) test duration stared when all the test fixtures reached 50°C. Temperature data was remotely monitored and checked daily.

4. POST TEST ANALYSIS

Post testing, the fracture surfaces were prepared for viewing with a digital light microscope. The pre-cracked fracture surface and any crack growth that occurred during crack threshold testing were marked with an oxide coating in an oven set to 300°C for 30 minutes. Post-test fatigue cracks were then grown using the same pre-cracking method as described in Section 2.3. This allowed for the crack growth experienced during the environmental exposure to be framed between the pre- and post-fatigue cracks. Test specimens were then broken open to view the fracture surfaces. The initial fatigue crack length was measured, and the stress intensity of each specimen was calculated using Eq. (2) from ASTM E1681.

4.1. TENSILE PROPERTIES

Tensile results of the bulk material and weld are included in Table 1. The yield strength of the bulk averaged 156 ksi and the tensile strength was 166 ksi. The yield strength of the material in the weld averaged 140 ksi with a tensile strength of 154 ksi.

4.2. FRACTURE TOUGHNESS

Fracture toughness test results are listed in Table 2. The plane-strain validity criteria in ASTM E399 section 9.1.4 was not satisfied for the bulk or weld specimens. Therefore, results could not be reported as the plane-strain fracture toughness K_{IC}, but rather the conditional fracture toughness result, K_Q. Additionally, the weld specimens failed ASTM E399 section 9.1.3 because of plastic deformation at the crack tip at failure. Further testing of fracture toughness for these weld specimens should be according to ASTM E 1820 [9] to calculate the J_{Ic}, critical elastic-plastic fracture toughness. The average K_Q for the bulk specimens was 45.0 ksi√in and the weld specimens was 49.0 ksi√in.

4.3. THRESHOLD STRESS INTENSITY FACTOR

Results of the stress intensity threshold testing per ASTM E1681 are listed in Table 3 (bulk) and Table 4 (weld). Bulk and weld specimens failed ASTM E1681 section 9.3.1 validity check for K_{IEAC} where Eq. (3) is less than B, a_0, and W-a_0. A less restrictive validity check for K_{EAC} was calculated per ASTM E1681 section 9.3.2, where Eq. 4 is less W-a_0.

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

$$2.5\left(\frac{K_{EAC}}{\sigma_{YS}}\right)^2 \quad (3)$$

$$\frac{4}{\pi}\left(\frac{K_{EAC}}{\sigma_{YS}}\right)^2 \quad (4)$$

The bulk material passes this criteria at stress intensities less than 43 ksi√in and the weld specimens pass this criteria at stress intensities less than 37 ksi√in. Plane-strain conditions would have been ideal but could not be achieved with these specimens due to the thickness constraints of the material provide for this test.

Six (6) bulk and six (6) weld samples have been tested and evaluated with propellant exposure. A third and final round is in work, and the results will be reported when available. The averaged threshold intensity factor environment-assisted cracking of the Ti 6Al-4V forged tank material when exposed to LMP-103S propellant was determined to be least 22.5 ksi√in and at least 36.2 ksi√in in the weld material.

4.4. Additional Threshold Stress Intensity Testing

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 for the recommended 1000-hour (42 day) test duration and further assess the un-wetted stress intensity factor. For this dry test series, two (2) bulk specimens were loaded at ~25 ksi√in, two (2) at ~35 ksi√in, and two (2) at ~40 ksi√in. A similar setup was used for the weld material with two (2) specimens at ~35 ksi√in, two (2) at ~40 ksi√in, and two (2) at ~45 ksi√in. This testing was executed at the 50°C temperature. Post evaluation, the dry control test indicated that one (1) bulk sample showed slight crack growth at a ~41 ksi√in, which was the highest load tested on the bulk samples. All other dry-test specimens showed no signs of crack growth in the absence of propellant. This testing showed a bulk material stress intensity threshold ~40 ksi√in. For the weld material, testing exhibited a stress intensity threshold ~ 42 ksi√in.

5. DAMAGE TOLERANCE ASSESSMENT

A damage tolerance, or crack growth assessment, is performed as part of the structural analysis/verification process for spaceflight propellant tanks. The means for this is NASGRO, a tool originally developed at NASA Johnson Space Center, now managed by Southwest Research Institute NASGRO comprises a suite of modules for crack propagation and fracture mechanics analyses. A crack propagation assessment is performed with knowledge of tank geometry (e.g., wall thickness and diameter), an initial crack size (determined through NDE inspection limitations), the associated number of fully reversed cycles at a known stress state, and specific crack growth material properties such as surface effective fracture toughness, K_{IE}. NASGRO, calculates a stress intensity factor, K, at the crack tip given the geometry and state of stress. If the crack propagates through a surface sufficiently such that the remaining material cannot support the net stress, or $K > K_{IE}$, the part is predicted to fail under the given stress-based cyclic loading.

While the surface fracture toughness value, K_{IE}, is derived from inherent properties of the material (measured in air at room temperature), additional testing can be performed to account for environmental effects. For this, the threshold stress intensity factor for environment assisted cracking, K_{EAC}, is determine through testing. For the work described herein, a specific set of K_{EAC} values were measured to account for the presence of the propellant LMP-103S when exposed to Ti 6Al-4V tank material. As an adjunct to the testing, a NASGRO crack propagation assessments was performed to investigate the effects of using K_{EAC} versus the standard Titanium K_{IE} value (50.0 ksi√in).

An ellipsoidal candidate tank made from two sections of Ti 6Al-4V material was selected. Rough dimensions are ~30 inches diameter, and ~50 inches in length. A fracture spectra service life table (stress vs. number of cycles) was developed for the tank. This accounts for all mission phases: proof and acceptance ground testing, transportation, launch, and on-orbit loading. Table 5 presents these various phases, number of cycles, and steady-state initial/final pressure values (columns 1-5). The table also presents the dynamic mechanical loading on the tank during the transportation and launch phases (columns 6-7). These are split into various steps as a function of the loading direction. Lateral loading is defined in the X/Y directions with the launch (axial) direction in Z. The large number of mechanical cycles for transportation are due to random vibration loads over three (3) days road transportation, while the smaller number of cycles for the launch phase are attributed to sine vibration input over just a few minutes.

Table 1. Tensile Testing Results [4]

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

Table 2. Fracture Toughness Results [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

Table 3. Stress Intensity Results – Bulk

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 propellant, but slight (<40 microns) crack growth due to overtest
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 propellant
B103	0.0925	0.1980	0.1053	23.24		PASS	No failure or crack growth after 1,000 hours of exposure to LMP-103S propellant
B105	0.0950	0.1985	0.1008	20.82		PASS	No failure or crack growth after 1,000 hours of exposure to LMP-103S propellant
B107	0.0930	0.1980	0.1034	22.47		PASS	No failure or crack growth after 1,000 hours of exposure to LMP-103S propellant
B108	0.0940	0.1970	0.1018	21.91		PASS	No failure or crack growth after 1,000 hours of exposure to LMP-103S propellant

Table 4. Stress Intensity Results – Weld

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 propellant
W102	0.0970	0.1930	0.1099	36.46		PASS	No failure or crack growth after 1,000 hours of exposure to LMP-103S propellant
W103	0.0935	0.1935	0.1098	37.45		PASS	No failure or crack growth after 1,000 hours of exposure to LMP-103S propellant
W104	0.0920	0.1910	0.1034	35.43		PASS	No failure or crack growth after 1,000 hours of exposure to LMP-103S propellant
W106	0.0950	0.1920	0.1083	36.71		PASS	No failure or crack growth after 1,000 hours of exposure to LMP-103S propellant
W107	0.0945	0.1920	0.1084	37.06		PASS	No failure or crack growth after 1,000 hours of exposure to LMP-103S propellant

The dynamic mechanical loads produce a smaller amount of induced tank wall stress versus pressurization. Note for these mechanical input phases, tank pressure remains nearly constant (0.5 psi conservative variation). Total stress values were estimated for the tank given the MEOP value of 350 psig associated with LMP-103S engine blowdown operation and associated residual manufacturing stresses. The 360 psig in the table represents a 10 psig upper tolerance for pressure testing. Dynamic loads are additive, and each total stress cycle is assumed fully reversed to remain conservative.

While many locations are normally evaluated for crack growth on a propellant tank, two areas were chosen for this study: one (1) in the dome area (parent Ti 6Al-4V material), and one (1) in the welded girth ring area (weld/HAZ Ti 6Al-4V material). For use in NASGRO, the various stress values were normalized by the maximum stress for each tank location (95.2 ksi in the dome, 54.8 ksi in the weld – both hoop stress). Table 5 also presents (columns 8-11) the initial (subscript '1') and final (subscript '2') normalized stress values for each phase at each location.

For the crack growth evaluation, NASGRO v10.11 was used. Based on the geometry, crack case SC30 was chosen: semi-elliptical surface crack (offset) in plate – univariant WF. For this case, only a uniform stress, normal to the crack opening, was employed (S_o). Thickness and initial flaw sizes varied depending on the location (see below), and width (W) was set to 10 inches, and crack offset (B) to 5 inches for all runs. From the NASGRO database, a STA Ti-6Al-4V forging material was chosen for the dome area and Ti 6Al-4V weld material for the weld/HAZ girth ring area.

Multiples NASGRO runs were performed and are summarized in Table 6. 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. First, a typical assessment was performed on the tank at the two locations using just the K_{IE} parameter and ignoring any environmental effects (K_{EAC}). These all show passing results under the required 4x service life (from Table 5). A subsequent set of runs activated the K_{EAC} check with the appropriate values (22.5 ksi√in and 36.2 ksi√in) for both locations. Likewise, these also show passing results for the 4x life. But it can be seen that for the dome area especially, the K_{max} value calculated at the crack almost exceeded the set K_{EAC} value, which showed environmental effects can reduce service life for an existing design.

As a sensitivity study, one final set of runs were performed to determine how much thinner each section could go before failure under the LMP-103S propellant environmental conditions. For this, thickness was adjusted as well as the resulting maximum stress (as stress scales with thickness when subjected to internal pressure). These results show failure ($K_{max} > K_{EAC}$) before 4x mission lives were completed for the dome area with just a 0.003in reduction in tank wall thickness. Due to the nature of radiographic NDE, smaller cracks can be detected through thinner sections (i.e., min. crack size is a function of weld thickness: $a_{min} = 0.7 \times t_{weld}$). So the girth weld area shows less sensitivity to K_{EAC} because of this.

Table 5. NASGRO Fracture Spectra

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

Table 6. NASGRO Results Summary

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

6. CONCLUSION

The threshold stress intensity factor for environment-assisted cracking was established for bulk and weld Ti 6AL-4V propellant tank material when exposed to LMP-103S propellant. Bulk material representing the Ti 6Al-4V tank forging was found to have a K_{EAC} of at least 22.5 ksi√in, and the weld material was found to be at least 36.16 ksi√in.

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 for the recommended 1000-hour (42 day) test duration and further assess the un-wetted stress intensity factor. This testing was executed at the 50°C temperature. This testing showed a bulk material stress intensity threshold at ~40 ksi√in. For the weld material, testing exhibited a stress intensity threshold at ~42 ksi√in.

The measured stress intensity threshold is slightly lower than the fracture toughness K_Q reported in Table 2. However, the Table 2 fracture toughness results from Table 2 were loaded for 1-hour versus the 1000-hour duration, and it is possible that there was some level of subcritical crack growth, but not failure.

Post determining the threshold stress intensity factor for environment-assisted cracking for the bulk and weld material, a basic damage tolerance assessment is performed assessment using NASGRO. This is a simplistic case to illustrate the process; however, and a rigorous structural analysis is required for spaceflight propellant tank safe-life demonstration to meet Range requirements. This would require looking at numerous tank locations, stress levels, and crack sizes (based on NDE).

Crack growth will occur at stress intensities near to the fracture toughness of the material. Future work is recommended in repeating this testing at higher loading For the bulk material, it is recommended to test at ~ 25 ksi√in (which is where the B101 sample showed slight crack growth). For the weld material, it is recommended to test at ~ 40 ksi√in.

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