Fracture Growth Testing of Titanium 6Al-4V in AF-M315E

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The Green Propellant Infusion Mission (GPIM) will demonstrate the performance of AF-M315E monopropellant in orbit. Flight certification requires a safe-life analysis of the titanium alloy fuel tank to ensure inherent flaws will not cause failure during the design life. Material property inputs for this analysis require testing to determine the stress intensity factor for environmentally-assisted cracking (K_{EAC}) of Ti 6Al-4V in combination with the AF-M315E monopropellant. Testing of single-edge notched specimens SE(B) representing the bulk tank membrane and weld material were performed in accordance with ASTM E1681. Specimens with fatigue pre-cracks were loaded into test fixtures so that the crack tips were exposed to the monopropellant at 50°C for a duration of 1,000 hours. Specimens that did not fail during exposure were opened to inspect the crack surfaces for evidence of crack growth. The threshold stress intensity value, K_{EAC}, is the highest applied stress intensity that produced neither a failure of the specimen during the exposure nor showed evidence of crack growth. The threshold stress intensity factor of the Ti 6Al-4V forged tank material when exposed to AF-M315E monopropellant was found to be at least 22.0 ksi√in. The stress intensity factor of the weld material was at least 31.3 ksi√in.

Nomenclature

a	=	crack length
a_0	=	initial crack length
B	=	specimen thickness
J_{Ic}	=	elastic-plastic fracture toughness
K	=	stress-intensity factor at the crack-tip in a linear-elastic body, measured in 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_{EAC}	=	stress intensity factor threshold for environmentally assisted crack growth
K_{IEAC}	=	stress intensity factor threshold for plane strain environmentally assisted crack growth
K_Q	=	critical stress intensity factor, a plane-strain loading condition
L	=	length from crack plane to center of gravity of counterweight
L_a	=	length from crack plane to center of gravity of moment arm
M	=	moment, $L*W_t+L_a*W_a$
P	=	force
R	=	stress ratio, a ratio of the maximum stress to the minimum stress during cyclic fatigue
σ_{YS}	=	yield strength determined in tensile with the 0.2% offset method
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

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W_t = weight of counterweight added to loading arm

I. Introduction

The Green Propellant Infusion Mission (GPIM), managed by Ball Aerospace and funded by NASA Marshall Space Flight Center (MSFC), will demonstrate the in-space performance of a new monopropellant, AF-M315E. Developed by the Air Force Research Laboratory (AFRL), AF-M315E provides a higher density with the same specific impulse as hydrazine. Because this hydroxylammonium nitrate blend has a lower vapor pressure than hydrazine, it does not require the same degree of personal protective equipment (PPE) during servicing. It is expected that this reduction in PPE will lower the cost of propellant handling. In flight, the propellant is contained in a pressurized tank on a spacecraft or satellite. A fracture mechanics analysis is required to verify the safe design life of the pressurized tank during launch. The objective of fracture mechanics analysis is to model operating stresses so that a preexisting flaw of an assumed maximum initial size will not grow to a critical size during the service life of the propellant tank. The analysis shows that any crack that would have been large enough to cause the tank to fail would have been seen during inspection. Inputs for this analysis include the crack growth properties of the tank material when exposed to the propellant.

Since NASA's Apollo program titanium alloy Ti 6Al-4V has been the material of choice for propellant pressure vessels because of its high strength to weight ratio and its resistance to corrosion. The structural integrity of Ti 6Al-4V pressure vessels has been studied since the late 1960's. Included in these studies was the sustained load flaw growth of the Ti 6Al-4V and welds of Ti 6Al-4V alloy. Crack growth testing was carried out using common propellants and oxidizers in use during the time period, which included hydrazine, monomethyhydrazine, Aerozine 50, and nitrogen tetroxide. The threshold stress intensity factor for environment-assisted crack growth (K_{EAC}) was determined through test. Since then, all pressurized propellant tanks used on NASA spacecraft have used these combinations of tank material and propellants. With the development of AF-315E monopropellant, testing is required to determine the K_{EAC} of the titanium tank when exposed to this new monopropellant.

The testing documented herein investigates the threshold stress intensity factor for environmentally-assisted cracking (K_{EAC}) of Ti 6Al-4V in combination with AF-M315E for input into a fracture mechanics analysis. A team of engineers at NASA's Kennedy Space Center (KSC), ATK Space Systems, Air Force Research Laboratories (AFRL) at Edwards Air Force Base, and Ball Aerospace have developed procedures and test hardware to perform this testing. Because the flight tank is fabricated by welding two hemispherical forgings into a sphere, testing will include specimens representing the bulk forging and the weld. Testing of the weld material will be especially important because the design of the tank precludes the possibility of post weld aging heat treatments. Testing will be performed according to ASTM E1681- *Standard Test Method for Determining Threshold Intensity Factor for Environment-Assisted Cracking of Metallic Materials*. Upon completion of the testing, the resultant stress intensity threshold values will be provided to ATK for analysis using NASGRO[1] fracture analysis software. Historically NASGRO fracture analysis has been performed used data from Ref. 2, which documents testing of uniaxially loaded fracture mechanics specimens containing part-through cracks. The crack tips of these specimens were exposed to hydrazine under a sustained load for 24 hours. Lewis and Kenny[2] also document design data recommendations for Ti 6Al-4V forgings and un-aged welds.

II. Procedure

The purpose of the testing is to produce stress intensity threshold values for Ti 6Al-4V in AF-M315E monopropellant in accordance with ASTM E1681[4]. For this test single-edge bend specimens, annotated as SE(B) specimens, were fatigued to grow sharp crack tips. SE(B) specimens were loaded into test fixtures so that the crack tips were exposed to the propellant at 50°C for a duration of 1,000 hours. This temperature represents the highest temperature that the flight tank is expected to experience in orbit and the worst case for corrosive effects of the monopropellant. The duration of the test was dictated by ASTM E1681. Upon completion of the exposure, SE(B) specimens, which did not fail, were marked with post-test fatigue cracks. Specimens were then opened to inspect the crack surfaces for evidence of growth during environmental exposure. The threshold stress intensity value, K_{EAC}, is the highest applied stress intensity that produced neither a failure of the specimens during the exposure nor showed evidence of crack growth.

A. Specimen Preparation

[4] ASTM E1681, *Standard Test Method for Determining the Threshold Stress Intensity Factor for Environmentally-Assisted Cracking of Metallic Materials.*

The test material, shown in Fig. 1 included a titanium Ti 6Al-4V forging and a weld verification ring. The Ti 6Al-4V forging was provided in the solution treated and aged (STA) condition to represent the bulk tank membrane. The weld verification ring was provided to represent the Ti 6Al-4V weldment on the GPIM tank.

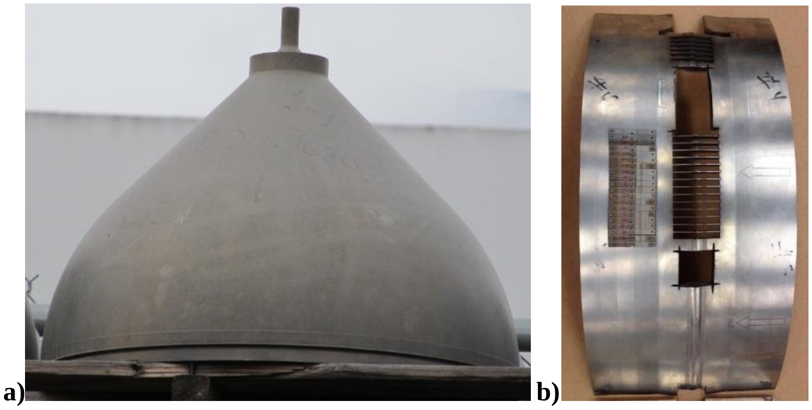

Figure 1. Ti 6Al-4V material. *SE(B) specimens were machined from the a) bulk forging and b) weld verification ring.*

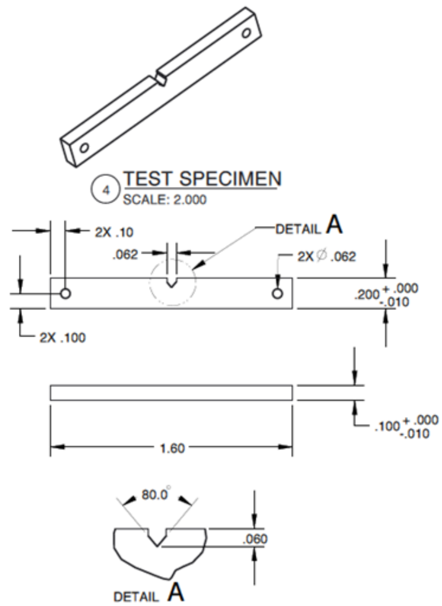

Figure 2. SE(B) specimen dimensions.

SE(B) specimens were machined to the dimensions shown in Fig. 2. Bulk specimens were cut from the forging so that cracks would grow in the L-S direction[5], 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 direction the weld solidification. Specimens were cut using a wire electrical discharge machine (EDM). The faces of the specimen were ground and polished to remove the recast layer. The polished surfaces enabled estimates of pre-crack length from the measurement of the sidewall cracks at the notch.

B. Tensile, Metallography, & Microhardness

It was necessary to determine the tensile properties, specifically the yield strength, of the materials 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 material and the weld. Sub-sized specimens were cut using the wire EDM. Gauge length was reduced from 1.0 inches to 0.75 inches because of the size of the sections available for testing. Bulk specimen were tested in the wrought direction and weld specimens were tested perpendicular to the direction of the weld solidification.

Metallographic specimens were prepared from the weld per ASTM E3[7] in order locate the notch of the SE(B) specimens and ensure that the fractures would be contained in the weld. To locate the heat affected zone (HAZ) of the weld, Vickers microhardness testing was performed with 500 gf load in accordance to ASTM E384[8].

C. Fatigue Pre-Cracking

Fatigue pre-cracks were induced at the notched SE(B) specimens using an MTS 810 servo-hydraulic load frame. A three-point bending test fixture in Fig. 3 was configured referencing ASTM E399 Annex 2 with a load span of 0.8 inches. 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 was either 110, 90, or 70 lbf. Using Eq. (1), the stress intensity was never above 15 ksi√in to prevent a plastic deformation at the crack tip. The fatigue crack length was monitored on the sidewalls of the specimen, as is shown in Fig. 3, using a Keyence digital stereomicroscope. The target length for the fatigue cracks was 0.10±0.01 inches. Specimens were cleaned prior to loading in the test fixtures per ASTM G1[9].

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[5] ASTM E399, *Standard Test Method for Linear-Elastic Plane-Strain Fracture Toughness K_{Ic} of Metallic Material*.
[6] ASTM E8, *Standard Test Methods for Tension Testing of Metallic Materials*.
[7] ASTM E3, *Standard Guide for Preparation of Metallographic Specimens.*
[8] ASTM E384, *Standard Test Method for Knoop and Vickers Hardness of Materials*.
[9] ASTM G1, *Practice for Preparing, Cleaning, and Evaluation Corrosion Test Specimens*.

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

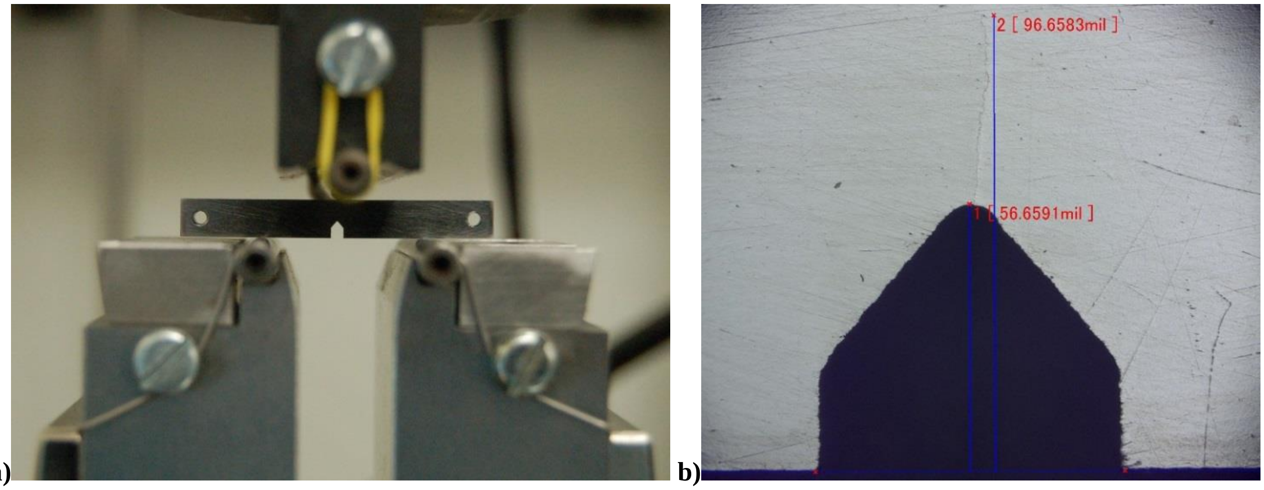
a) b)


Figure 3. SE(B) specimens. *a) Three-point bend fixture with SE(B) specimen. b) Fatigue crack growth monitoring with a stereomicroscope.*

D. Fracture Toughness

Fracture toughness testing was performed on specimens representing both the bulk tank material and the weld material. Testing was performed per ASTM E399. Results were used to design and build test fixtures and weights for the threshold stress intensity testing that followed.

E. Propellant Exposure

AFRL at Edwards Air Force Base designed test fixtures for loading the specimens while they are exposed to the AF-M315E monopropellant in an oven set to 50°C for 1,000 hours. The cantilever bending apparatus shown in Figure 4 was designed to apply stress intensities up to 80% of the fracture toughness. The fixture was designed such that the notch and crack were surrounded by a flask, which contained the AF-M315E monopropellant. The flask contained through holes for the specimen which were sealed with a rubberized sealant. The test fixtures were designed to hold twelve specimens that were dead weight loaded, exposed to the propellant, and placed in an oven for the duration of the test.

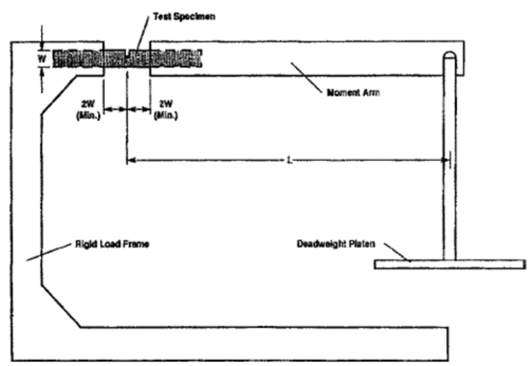


Figure 4. Loading Fixture from ASTM E1681.

F. Post Test Analysis

After exposure, the fracture surfaces were opened for view using the stereomicroscope. The pre-cracked fracture surface and any crack growth form the threshold testing were marked with an oxide coating in an oven set to 570°C for 30 minutes. Post-test fatigue cracks were then grown using same the pre-cracking method. This allowed for crack growth 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 lenghts were measured and the stress intensity of each specimen was calculated using Eq. (2) from ASTM E1681.

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

G. Additional Threshold Stress Intensity Testing

To validate results of the initial investigation, additional testing was performed using ASTM E1681 fixtures, but without exposure to propellant and at ambient laboratory conditions. Fixtures as described in ASTM E1681 were designed and built at NASA KSC. A sample of SE(B) specimens were pre-cracked and incrementally loaded until failure. These results were used to compare to the fracture toughness values and the failures encountered during the threshold stress intensity testing in the monopropellant.

III. Results

Two rounds of twelve SE (B) specimens have been exposed to the AF-M315E monopropellant for the duration of the 1,000-hour test. After testing, twelve of these specimens were evaluated post-test according to ASTM E1681.

A. Tensile Properties, Metallography & Microhardness

Tensile results of the bulk material and weld are displayed in Table 1. The yield strength of the bulk averaged 156.3 ksi and the tensile strength was 165.5 ksi. The yield strength of the material in the weld averaged 140.4 ksi with a tensile strength of 153.6 ksi. The micrograph of the weld, along with the Vickers microhardness numbers are shown in Fig. 5.

B. Fracture Toughness Results

Fracture toughness test results are listed in Table 3. The plane-strain validity criteria in ASTM E399 section 9.1.4 was not satisfied for neither the bulk nor the weld specimens. Results could not therefore be reported as K_{Ic} but rather K_Q. Additionally, the weld specimens failed ASTM E399 section 9.1.3 because of ductility. Further testing of fracture toughness for these weld specimens should be according to ASTM E 1820[10] 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.

C. Threshold Stress Intensity Results

Results of the stress intensity threshold testing per ASTM E1681 are listed in Table 4. 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. 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 in with these specimens due to the thickness constraints of the material provide for this test.

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

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

Eight of the twelve specimens from the first round of testing failed during dead weight load application. The remaining four specimens showed evidence of crack growth at the fatigue crack. Example micrographs can be seen in Fig. 6.

The second round of twelve specimens produced no specimen failures. Crack growth is not expected in these specimens since a twenty-four hour preliminary test run was conducted with three specimens at high stress intensity values with no crack growth detected. The facture surface of the SE(B) specimen from this preliminary test are shown in Fig. 7.

D. Additional Threshold Stress Intensity Results

Results from the threshold stress intensity testing at ambient laboratory conditions are shown in Table 5, with a photograph of the load fixtures shown in Fig. 8. The bulk material specimens averaged 45.6 ksi√in and the weld specimens averaged 50.8 ksi√in.

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[10] ASTM E1820, *Standard Test Method for the Measurement of Fracture Toughness.*

IV. Conclusion

The threshold stress intensity factor for environment-assisted cracking was determined for titanium alloy GPIM flight tanks when exposed to AF-M315E monopropellant. Material representing the bulk titanium Ti 6Al-4V forging was found to have a K_{EAC} of at least 22.0 ksi√in, and the weld material was found to be at 31.3 ksi√in. Plane-strain conditions would have been ideal but could not be achieved due to the thickness constraints of the material provide for this test. However, the test specimens were thicker than the tank wall of the GPIM flight tank and are therefore considered a conservative stress intensity threshold result.

Stress threshold testing of the bulk titanium, but with no exposure to the propellant and at ambient laboratory conditions was 45.6 ksi√in. This value is comparable to the fracture toughness, K_Q, measured according to ASTM E399, where the bulk specimens averaged 45.0 ksi√in. It is noted that during the first round of ASTM E1681 testing, the average stress intensity that caused failure of the bulk specimens was 45.9 ksi√in.

The stress threshold testing of the unaged weld material, but with no exposure to the propellant and at ambient laboratory conditions was 50.8 ksi√in. This value is also comparable to the fracture toughness, K_Q, measured according to ASTM E399, where the weld specimens averaged was 49.0 ksi√in. The unaged Ti 6Al-4V weld metal was not found to be extremely susceptibility to crack growth in AF-M315E monopropellant as it was concluded to be in hydrazine according to Ref. 2. Other factors that would have reduced the threshold stress intensity factor of the weld material include the quality of the weld and the direction of crack growth in the weld metal.

ASTM E1681 stress threshold testing criteria does not produce evidence to exonerate any environmental test media of accelerated crack growth. Subcritical growth from loading of the crack tip at stress intensities close to the fracture toughness of the material occur in any environment. Future work is recommended to further refine the threshold stress intensity factor for environment-assisted cracking of Ti 6Al-4V in AF-M315E monopropellant. Additional testing of the bulk material between stress intensities in the range of 22-35 ksi√in and weld material in the range of 33-49 ksi√in will result in an increased factor of safety for the safe-life analysis of the GPIM flight tanks.

Appendix

Table 1. Results of Tensile Testing. *Tensile testing was performed to obtain the yield strength. Yield strength is used in the validity test 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

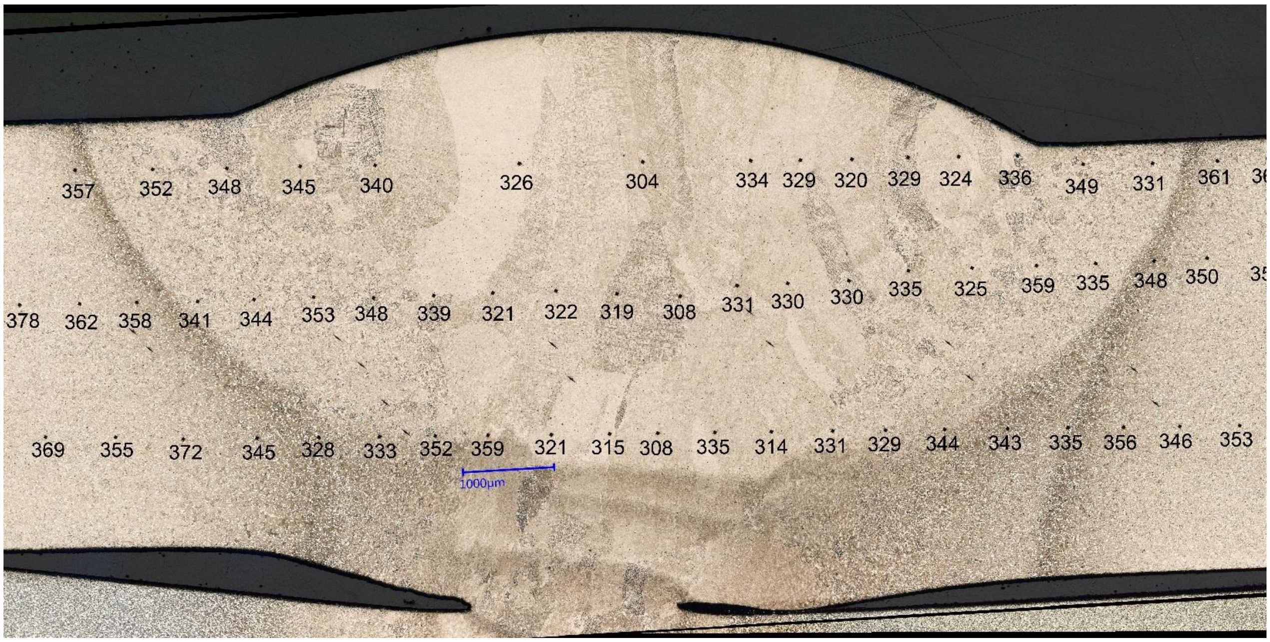

Figure 5. Micrograph of weld. *Polished section of weld etched with Kroll's reagent. Vickers microhardness (HV) numbers tested with a 500 gf.*

Table 2. Results of fracture toughness testing. *Fracture toughness was tested per ASTM E399.*

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. Results from first round of stress intensity threshold testing. *Stress intensity test values caused failure or crack growth in all test specimens.*

Material	Specimen	Specimen Thickness, *B* (in)	Specimen Width, *W* (in)	Initial Crack Length, a_0 (*in*)	Applied Moment, *M* (in*lb)	Stress intensity, K_{EAC} (ksi√in)	Test Result
Bulk	B08	0.0955	0.1970	0.0930	29.3	36.4	Crack growth detected after 1000 hours exposure
Bulk	B16	0.0950	0.1965	0.0942	29.3	37.6	Crack growth detected after 1000 hours exposure
Bulk	B20	0.0950	0.1965	0.0965	29.3	38.8	Crack growth detected after 1000 hours exposure
Bulk	B06	0.0950	0.1970	0.0924	31.5	38.9	Immediate fracture upon loading
Bulk	B11	0.0950	0.1970	0.0945	31.5	40.2	Crack growth detected after 1000 hours exposure
Bulk	B15	0.0950	0.1970	0.0984	31.5	42.6	Immediate fracture upon loading
Bulk	B14	0.0950	0.1960	0.0956	33.6	44.3	Immediate fracture upon loading
Bulk	B12	0.0955	0.1970	0.0953	35.8	46.0	Immediate fracture upon loading
Bulk	B19	0.0950	0.1960	0.0956	35.8	47.1	Immediate fracture upon loading
Bulk	B10	0.0950	0.1965	0.0969	35.8	47.7	Immediate fracture upon loading
Bulk	B22	0.0950	0.1965	0.1010	33.7	47.9	Fracture approx. 5 minutes after loading
Bulk	B18	0.0955	0.1965	0.1074	33.7	52.8	Immediate fracture upon loading

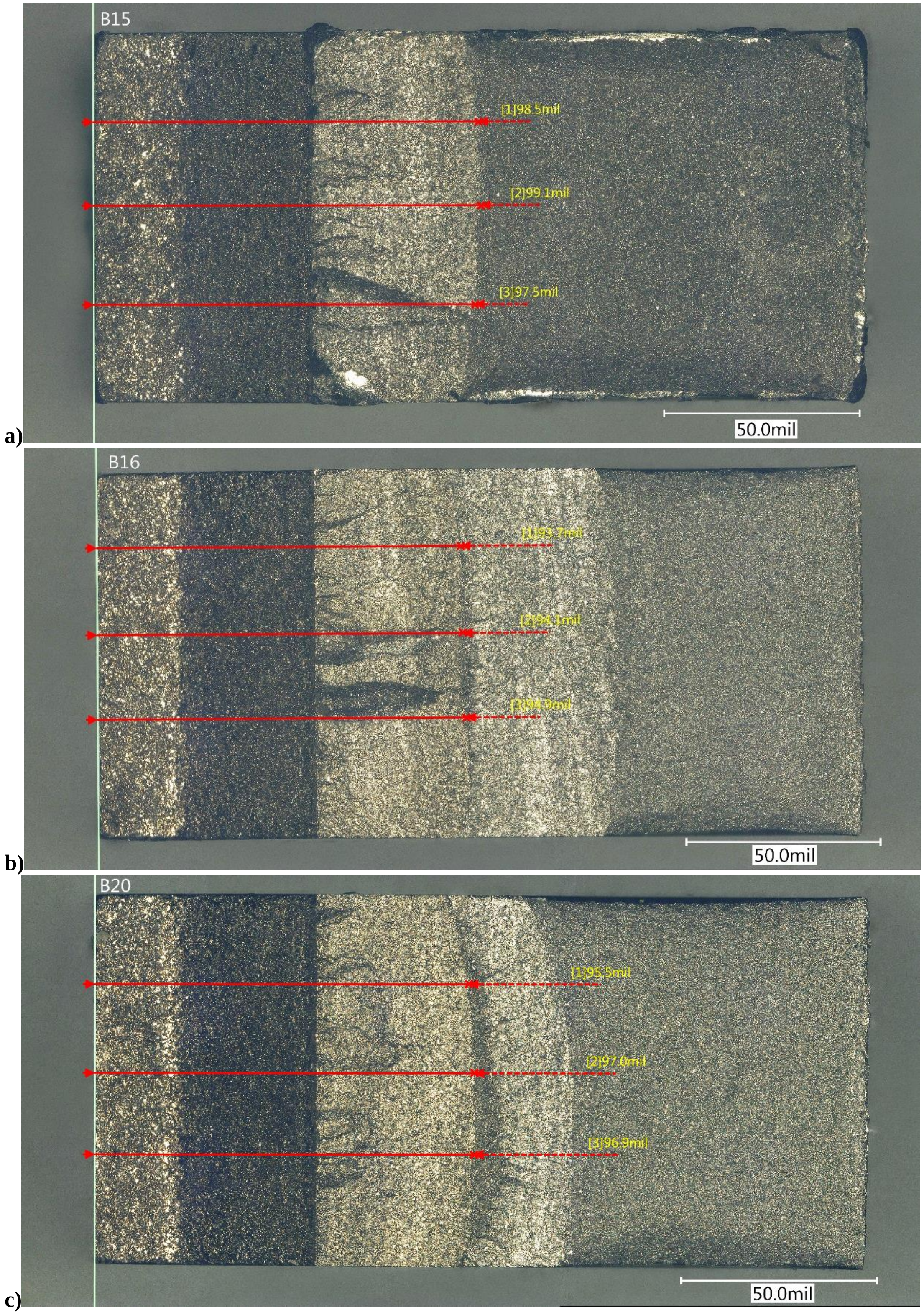

Figure 6. Fracture surfaces of bulk specimens. *The length of the fatigued pre-crack is annotated on specimen a) B15, which failed immediately after application of the dead weight load. Specimen b) B16 and c) B20 survived the 1,000 hours test but showed evidence of crack growth*.

Table 4. Results from second round of stress intensity threshold testing. *No failures after 1,000 hours of exposure, however specimens have not yet been inspected for crack growth.*

Material	Specimen	Specimen Thickness, *B* (in)	Specimen Width, *W* (in)	Predicted Crack Length, $a_{0\ (in)}$	Stress Intensity, K_{EAC} (ksi√in)	Test Result
Bulk	B26	0.0950	0.1970	0.1046	22.0	No failure after 1,000 hours exposure, crack growth not yet evaluated
Bulk	B27	0.0950	0.1970	0.1024	22.0	No failure after 1,000 hours exposure, crack growth not yet evaluated
Bulk	B28	0.0950	0.1965	0.0990	22.0	No failure after 1,000 hours exposure, crack growth not yet evaluated
Bulk	B29	0.0950	0.1975	0.1034	22.0	No failure after 1,000 hours exposure, crack growth not yet evaluated
Weld	W08	0.0910	0.1980	0.1043	31.3	No failure after 1,000 hours exposure, crack growth not yet evaluated
Weld	W10	0.0920	0.1980	0.1070	31.4	No failure after 1,000 hours exposure, crack growth not yet evaluated
Weld	W12	0.0930	0.1990	0.1042	31.3	No failure after 1,000 hours exposure, crack growth not yet evaluated
Weld	W13	0.0915	0.1980	0.1018	31.3	No failure after 1,000 hours exposure, crack growth not yet evaluated
Weld	W14	0.0920	0.1985	0.1063	31.3	No failure after 1,000 hours exposure, crack growth not yet evaluated
Weld	W15	0.0925	0.1980	0.1018	31.3	No failure after 1,000 hours exposure, crack growth not yet evaluated
Weld	W16	0.0920	0.1985	0.1046	31.4	No failure after 1,000 hours exposure, crack growth not yet evaluated
Weld	W17	0.0925	0.1990	0.0992	31.4	No failure after 1,000 hours exposure, crack growth not yet evaluated
Weld	W18	0.0935	0.1980	0.1081	32.9	No crack growth after 24 hours of loading in air (no propellant)
Weld	W19	0.0920	0.1975	0.1095	33.0	No crack growth after 24 hours of loading in air (no propellant)
Weld	W20	0.0930	0.1975	0.1053	33.0	No crack growth after 24 hours of loading in air (no propellant)

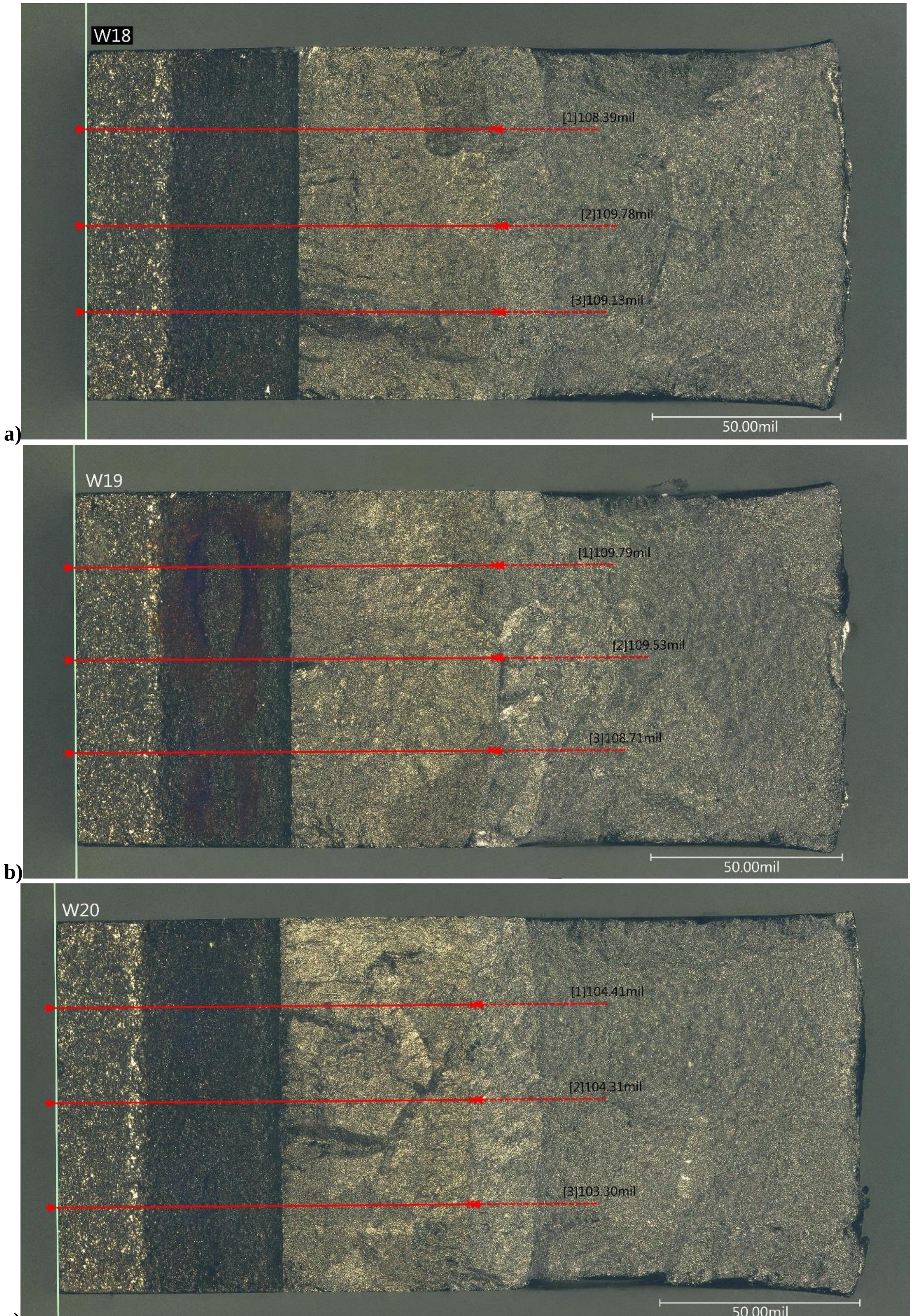

Figure 7. Fracture surfaces of weld specimens. *The length of the fatigued pre-crack in shown marked with the straw-colored oxide on specimens a) W18, b) W19, and c) W20. There was no crack growth after loaded these specimens for 24 hours.*

Table 5. Results additional stress threshold testing. *Threshold fracture toughness values are the highest applied moment which did not cause specimen failure.*

Material	Specimen	Specimen Thickness, *B* (in)	Specimen Height, *W* (in)	Initial Crack Length, a_0 (in)	Stress intensity, *K* (ksi√in)	Result
Bulk	BX0	0.0950	0.1945	0.1239	47.7	No failure after 1 hour
					51.6	Immediate failure
Bulk	BX1	0.0915	0.1960	0.1180	46.1	No failure after 1 hour
					50.2	Failure after 3 min
Bulk	BX2	0.0915	0.1960	0.1121	45.0	No failure after 1 hour
					48.3	Failure after 3 min
Bulk	B23	0.0950	0.1945	0.0986	43.5	No failure after 1 hour
					56.4	Immediate failure
Weld	W07	0.0915	0.1975	0.1049	47.5	No failure after 1 hour
					61.7	Immediate failure
Weld	W09	0.0925	0.1985	0.1037	49.5	No failure after 1 hour
					54.4	Fracture within 5 min
Weld	W06	0.0910	0.1980	0.1034	55.5	No failure after 1 hour
					60.1	Immediate failure

Figure 8. ASTM E1681 loading fixture. *SE(B) specimens were incrementally loaded until failure.*

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