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Stress Corrosion Evaluation of Various Metallic Materials for the International Space Station Water Recycling System

P.D. Torres
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March 2015

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Space Administration

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LIST OF ABBREVIATIONS, ACRONYMS, AND SYMBOLS

√	surface finish (arithmetic average roughness value)
A/C	air cool
Al	aluminum
AMS	Aerospace Material Specification
ASTM	American Society for Testing and Materials
ATI	Allegheny Technologies Incorporated
Bi	bismuth
C	carbon
Cb	columbium
Co	cobalt
Cr	chromium
Cu	copper
DI	deionized (water)
E	modulus of elasticity (Young's Modulus)
ECLSS	Environmental Control and Life Support System
EL	elongation
ELI	extra low interstitial
Fe	iron
Gr	grade
H	hydrogen
HRC	Rockwell C hardness
ISS	International Space Station
Mg	magnesium

LIST OF ABBREVIATIONS, ACRONYMS, AND SYMBOLS (Continued)

MIL	military
Mn	manganese
Mo	molybdenum
MSFC	Marshall Space Flight Center
Msi	megapounds per square inch
N	nitrogen
NaCl	sodium chloride
Nb	niobium
Ni	nickel
O	oxygen
P	phosphorus
Pb	lead
pretreat	pretreatment
R	radius
RA	reduction in area
S	sulfur
SCC	stress corrosion cracking
Si	silicon
Sn	tin
Ta	tantalum
Ti	titanium
Ti-6-4	Ti-6Al-4V
TiCP	titanium commercially pure
UPA	Urine Processing Assembly
UTS	ultimate tensile strength

LIST OF ABBREVIATIONS, ACRONYMS, AND SYMBOLS (Continued)

UTS_f	final ultimate tensile strength (after exposure)
UTS_i	initial ultimate tensile strength (average for nonexposed specimens)
V	vanadium
VAR	vacuum arc remelting
W	tungsten
Y	yttrium
YS	yield strength (0.2% offset)
Zr	zirconium

TECHNICAL MEMORANDUM

STRESS CORROSION EVALUATION OF VARIOUS METALLIC MATERIALS FOR THE INTERNATIONAL SPACE STATION WATER RECYCLING SYSTEM

1. INTRODUCTION

The high cost of carrying water into space to be used at the International Space Station (ISS) generated the need to manufacture a water-recycling system to process urine and make it suitable for human consumption. For years, the Environmental Control and Life Support System (ECLSS) Urine Processing Assembly (UPA) has used sulfuric acid as one of the ingredients to pretreat the urine. However, the formation of crystals, believed to be associated with the use of this acid, was causing some problems. Phosphoric acid was then considered as a candidate to replace sulfuric acid.

Because of this change in formulation of the pretreatment for processing the urine, a test program was undertaken at the Marshall Space Flight Center (MSFC) Materials and Processes Laboratory to perform various types of materials evaluations, including a stress corrosion characterization of six metallic materials: Inconel® 625, Hastelloy® C276, titanium commercially pure (TiCP), titanium 6Al-4V (Ti-6-4), Ti-6-4 extra low interstitial (ELI), and Cronidur® 30. The goal of this work was to determine if these materials have adequate stress corrosion resistance when exposed to the ECLSS UPA fluids.

The first five listed were found resistant to stress corrosion based on no failures, metallography, and no reduction in load-carrying ability. As for Cronidur 30, though no failures occurred and metallography did not indicate stress corrosion cracking (SCC), several specimens experienced reduction in load-carrying ability (up to 42% in the brine). This deficiency is not expected to have an influence on the performance of this alloy as long as it is used in compression, but there are some limitations on its use for applications where sustained tensile stresses are involved.

2. DEFINITION

2.1 Stress Corrosion

Stress corrosion may be defined as the combined action of sustained tensile stress and corrosion to cause premature failure of a susceptible material. Certain metallic materials are more susceptible than others. If a susceptible material is placed in service in a corrosive environment under tension of sufficient magnitude, and the duration of service is sufficient to permit the initiation and growth of cracks, failures can occur at a stress lower than the material would normally be expected to withstand.

3. EXPERIMENTAL PROCEDURE

3.1 Materials Evaluated

A description of the alloys evaluated in this test program is presented in table 1. This information was obtained from the materials certifications (shown in app. A) and includes applicable specifications for the materials, form, heat treatment, alloy producer, heat number, hardness, and heat chemistry.

Table 1. Description of the test materials.

Inconel 625 (Pyromet 625): Applicable specifications: AMS 5666 Rev F, ASTM B446-03 (2008) (grade 1) Form: 0.375-in-diameter bar Heat treat: Hot isostatic temperature alloy annealed ground Company: Carpenter Heat No.: 600213 Hardness as shipped: 29 HRC Heat chemistry (wt%): 0.04C, 0.06Mn, 0.09Si, 0.004P, 0.001S, 22.34Cr, 60.69Ni, 8.81Mo, 0.06Co, 0.15Al, 0.28Ti, 3.58Cb, 0.01Ta, 3.59Cb, 3.78Fe
Hastelloy C276 (Nickelvac C-276): Applicable specifications: AMS 5750C, ASTM B574-2006-1 Form: 0.375-in-diameter round bar, centerless ground surface Heat treat: 2050 °F, 30 minutes, water quenched (solution annealed) (heat treat code 2050A) Company: ATI Allvac Heat No.: 91KF Hardness as shipped: 23 HRC Heat chemistry (wt%): 0.004C, <0.0003S, 0.51Mn, 0.02Si, 15.07Cr, 15.22Mo, 0.02Co, <0.01Ti, 0.18Al, <0.01Zr, 6.32Fe, 0.02Cu, 59.14Ni, <0.004P, 0.03Cb, <0.01Ta, 3.24W, 0.20V, 0.04Cb, 0.19(Ti+Al), 59.16(Ni+Co) Traces: <0.00001Bi, <0.0001Pb, <0.0005Sn, <0.001O, 0.0047N
TiCP (Titanium Commercially Pure): Applicable specifications: AMS 4921 Rev L, ASTM B348, Gr4, Rev: 09, MIL-T-9047 Gr4 Rev: G Form: Centerless ground 0.375-in-diameter round bar (melt method was 2-VAR) Heat treat: Annealed 1300 °F 1 hour A/C (per MIL-H-81200)—as shipped Company: Dynamet (A Carpenter company); melt source was Timet Heat No.: H16512 Hardness: 24 HRC Heat average chemistry (top and bottom values were averaged) (wt%): 0.048C, 0.135Fe, 0.375O, 0.008N, <0.05 others each, <0.20 others total, balance Ti
Ti-6-4 (Titanium 6Al-4V): Applicable specifications: AMS 4928 (2007), ASTM F 136 Rev 12, AMS 4930 Rev G, ASTM B348 Gr 23 Rev 11, AMS 6932 Rev A, MIL-T-9047 Rev G, AMS 6931 Rev B, ASTM F 1472 Rev 08 Form: 0.375-in centerless ground round bar (melt method was 3-VAR) Heat treat: Material was annealed in accordance with MIL-H-81200B Company: Dynamet (A Carpenter Company); melt source was Timet Heat No.: H18003 Hardness: 34 HRC Heat average chemistry (top and bottom values were averaged) (wt%): 6.035Al, 0.030C, 0.185Fe, 0.0095N, 0.115O, 4.08V, <0.0004Y, Others each <0.10, Others total <0.30, Balance Ti

Table 1. Description of the test materials (Continued).

Ti-6-4 ELI (Ti-6-4 extra low interstitial): Applicable specifications: AMS 6932 Rev A, ASTM F136 Rev 12, ASTM B348 Gr23 Rev 11, AMS 4930 Rev G, MIL-T-9047 Rev G Form: 0.375-in-diameter centerless ground bar (melting method was 3-VAR) Heat treat: Material was annealed in accordance with MIL-H-81200B Company: Dynamet (A Carpenter company); melt source was Timet Heat No.: H18826 Hardness: 35 HRC Heat average chemistry (top and bottom values were averaged) (wt%): 6.07Al, 0.0285C, 0.18Fe, 0.0065N, 0.13O, 4.13V, <0.0004Y, 0.0022H, Others each <0.10, Others total <0.30, Balance Ti
Cronidur 30: Applicable specifications: AMS 5898 Form: 0.7165-in-diameter rod Heat treatment (per AMS 5898A, sections 3.4.6 to 3.4.6.1): Harden at 1925 ± 25 °F/30 ± 3 min in a neutral atmosphere, quench in oil to room temperature, temperature at 350 ± 10 °F/60 min ± 5, subzero cool to –100 ± 20 °F/2 ± 0.25 hours, warm in air to room temperature Heat No.: 32012 Hardness: >58 HRC Chemistry per AMS 5898A (wt%): 0.28–0.34C, 0.30–0.60Mn, 0.30–0.80Si, 0.020PMax, 0.010SMax, 14.5–16.0Cr, 0.95–1.10Mo, 0.35–0.44N, 0.30NiMax

Note: Alternate name shown in parentheses.

3.2 Test Matrix

A stress corrosion test matrix showing number of specimens and how they were allocated to various types of tests is presented in table 2.

Table 2. Stress corrosion test matrix.

Material	No. of Samples	Remarks
Inconel 625, Hastelloy C276, TiCP, Ti 6-4, and Ti-6-4 ELI	60 (12 samples/alloy per figure 1(a))	For each alloy: 3 for tensile data 4 in pretreat (3 @ 75% YS, 1 @ 0% YS) 4 in brine (3 @ 75% YS, 1 @ 0% YS) 1 in DI water
Cronidur 30 (hardened to Rockwell C 58 minimum, as for bearings)	33 samples per figure 1(b)	3 for tensile data 10 in pretreat (3 @ 50 ksi, 3 @ 25 ksi, 3 @ 15 ksi, and 1 w/o stress) 10 in brine (3 @ 50 ksi, 3 @ 25 ksi, 3 @ 15 ksi, and 1 w/o stress) 3 for salt fog test @ 25 ksi (for comparison) 3 for 3.5% NaCl alternate immersion test at 25 ksi (for comparison) 3 for high humidity test at 25 ksi (for comparison) 1 in DI water

Total number of round tensile specimens: 93

3.3 Specimen Configurations

For the first five alloys listed in table 2, 12 specimens per alloy were fabricated per figure 1(a). Since Cronidur 30 was expected to be more susceptible than the rest of the materials, 33 specimens were fabricated for a more thorough evaluation. Configuration shown in figure 1(b) was used for machining the Cronidur 30 specimens. This configuration has a bigger size of threads than the configuration used for the other materials, which can prevent failures in the threaded portion of the specimen. The shoulder is also larger to prevent failures out of the gauge length.

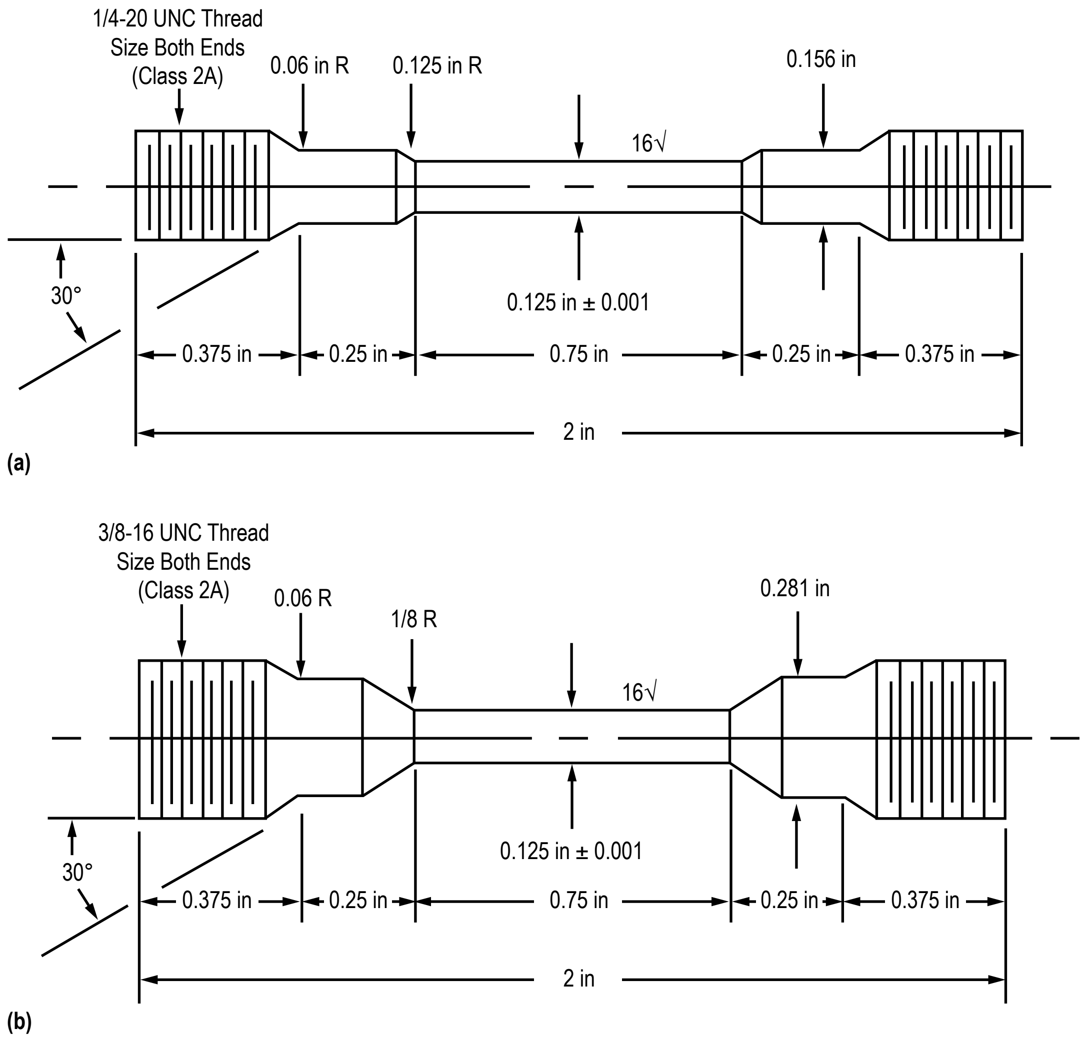
3.4 Tensile Tests of Specimens As Received

Three specimens from each alloy were tensile tested as received and the results obtained are summarized in table 3. Detailed results of the tensile tests are presented in appendix B. If the results of elongation and reduction in area are used to sort the alloys from most ductile to least ductile, the metals can be arranged in the following order: Hastelloy C276, Inconel 625, TiCP, Ti-6-4 ELI, Ti-6-4, and Cronidur 30. Notice the low ductility values of Cronidur 30, 2.2% elongation and 1.6% reduction in area, compared to the values for other alloys. Averaged Cronidur 30's ultimate tensile strength and yield strength (YS) values of 300.4 ksi and 252.7, respectively, are significantly higher than the values for the rest of the materials included in this evaluation. The Rockwell C hardness (HRC) for this material after hardening was more than 58.

Table 3. Averaged tensile data for the test materials.

Alloy Designation	UTS (ksi)	YS (ksi)	EL (%)	RA (%)	E (Msi)
Inconel 625	136.0	77.7	61.3	48.5	28.1
Hastelloy C276	120.7	67.0	69.1	60.4	31.8
TiCP	110.9	91.4	37.4	42.8	15.1
Ti-6-4	156.3	138.5	17.3	33.4	15.1
Ti-6-4 ELI	157.2	138.7	19.6	36.2	16.0
Cronidur 30	300.4	252.7	2.2	1.6	29.3

Notes:
- Values shown are the averages of three samples.
- Tensile data were obtained at MSFC (EM10) and presented in appendix B for individual samples.
- UTS: ultimate tensile strength, YS: yield strength, EL: % elongation, RA: % reduction in area, E: modulus of elasticity (Young's Modulus)
- Heat treatment is shown in table 1.



Notes:
(1) Tolerances: ±0.005 in, except otherwise specified.
(2) Surface finish (arithmetic average roughness value): 16 μin for the reduced section, 32 μin for the rest.
(3) Thread dimensions must be as specified. Measurement by fabricator is mandatory.
(4) No undercutting of radii permitted.
(5) Gauge section to be concentric with axis within 0.002 in total indicator reading (gauge section of the tensile cannot have more than 0.002 in total run-out) and parallel.
(6) No file marks or nicks permitted within gauge section.
(7) Drawing not to scale.
(8) Configuration (a) was used for five of the six materials tested. Configuration (b) was used for Cronidur 30 in order to obtain a larger size of threads and shoulder.

Figure 1. Round tensile specimen configurations.

3.5 Stressing of the Specimens

After obtaining the tensile data, the strain corresponding to the desired stress levels shown in table 2 were obtained and the specimens were stressed by using the stressing device shown in figure 2(a). The various components of the stressing fixtures are identified in the schematic diagram shown in figure 2(b). The document associated with this testing technique is the American Society for Testing and Materials (ASTM) G49 (Standard Practice for Preparation and Use of Direct Tension Stress-Corrosion Test Specimens).[1] In this method, the specimen is assembled into the stressing fixtures and an extensometer component is attached on the specimen reduced section. Two sidebars are then pushed toward the center by means of the device (see fig. 2(b)). The strain is measured by obtaining the difference between the initial and final readings. Representative stress corrosion specimens after they were loaded and before exposure are presented in figure 3.

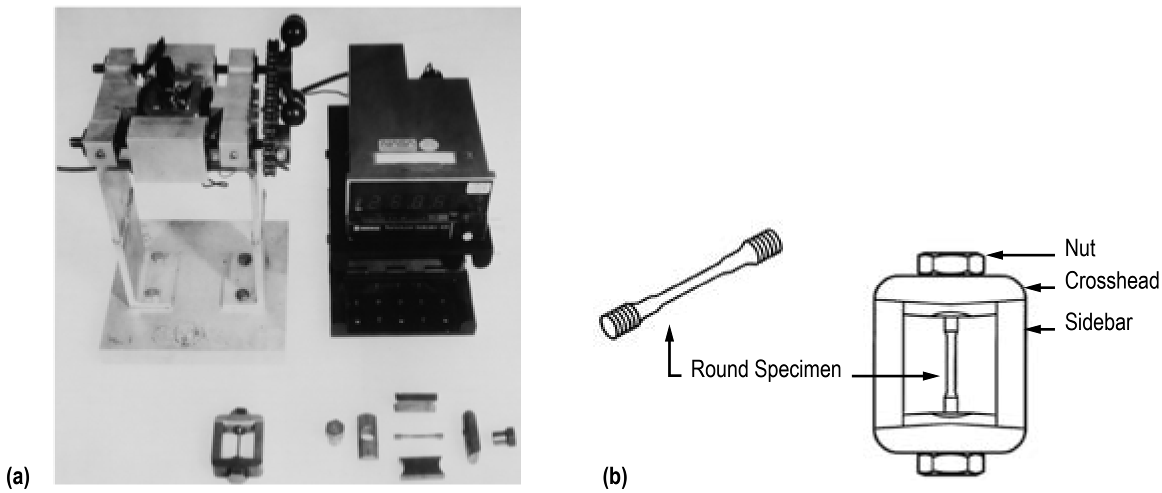


Figure 2. Stressing device and accessories: (a) Stressing device and (b) constant strain round specimen and frame assembly.

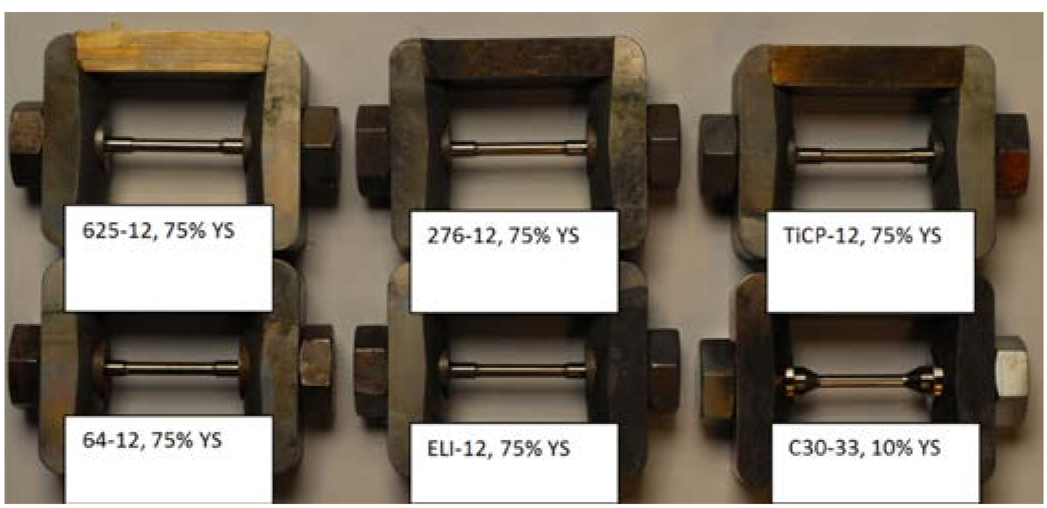


Figure 3. Representative assembled and loaded stress corrosion specimens before test.

3.6 Test Environments and Equipment

The stress corrosion testing was conducted using both phosphoric acid-based ECLSS pretreatment (pretreat) and brine solutions. The pretreat, which contains phosphoric acid and small amounts of chromic acid, has a pH in the vicinity of 2. Appendix C shows the formulas used for preparation of the reformulated pretreat and the baseline pretreat. The brine was obtained by distillation of the pretreat, which removed part of the water resulting in a more concentrated solution. One control sample from each alloy was exposed to deionized (DI) water. Exposure to the three environments—pretreat, brine, and DI—was carried out by completely immersing the specimens in the liquids contained in plastic containers and exposing them up to 1 year.

Cronidur 30, a bearing material, was expected to exhibit some degree of susceptibility because of its high hardness (HRC 58), therefore this material was further evaluated in three additional environments:

(1) High humidity in a cabinet that maintained a relative humidity within an approximate range of 85% to 95% at 95 ± 3 °F (Filter & Pump Manufacturing Co. Corrosion Test Cabinet Type 411.1 ACD, serial No. S-6310, NASA property No. 1535092).

(2) 5% salt spray at 95 ± 3 °F per ASTM B117[2] (by using Filter & Pump Manufacturing Co. Corrosion Test Cabinet type 411.1 ACD, serial No. 6198, NASA property No. G80024).

(3) 3.5% NaCl alternate immersion per ASTM G44[3] by using an in-house-built Ferris wheel type apparatus. The Ferris wheel apparatus allows the specimens to stay in the salt solution for 10 minutes of every hour, followed by a 50-minute drying cycle. These cycles are repeated for the duration of the test.

The alternate immersion method is the preferred method to evaluate metallic materials for stress corrosion cracking to eventually rate them in MSFC-STD-3029,[4] which is the baseline document used by NASA and contractors. For additional details about the 5% salt spray and 3.5% NaCl alternate immersion methods, see ASTM B117 and G44, respectively. Photographs related to the test methods described are represented in figure 4.

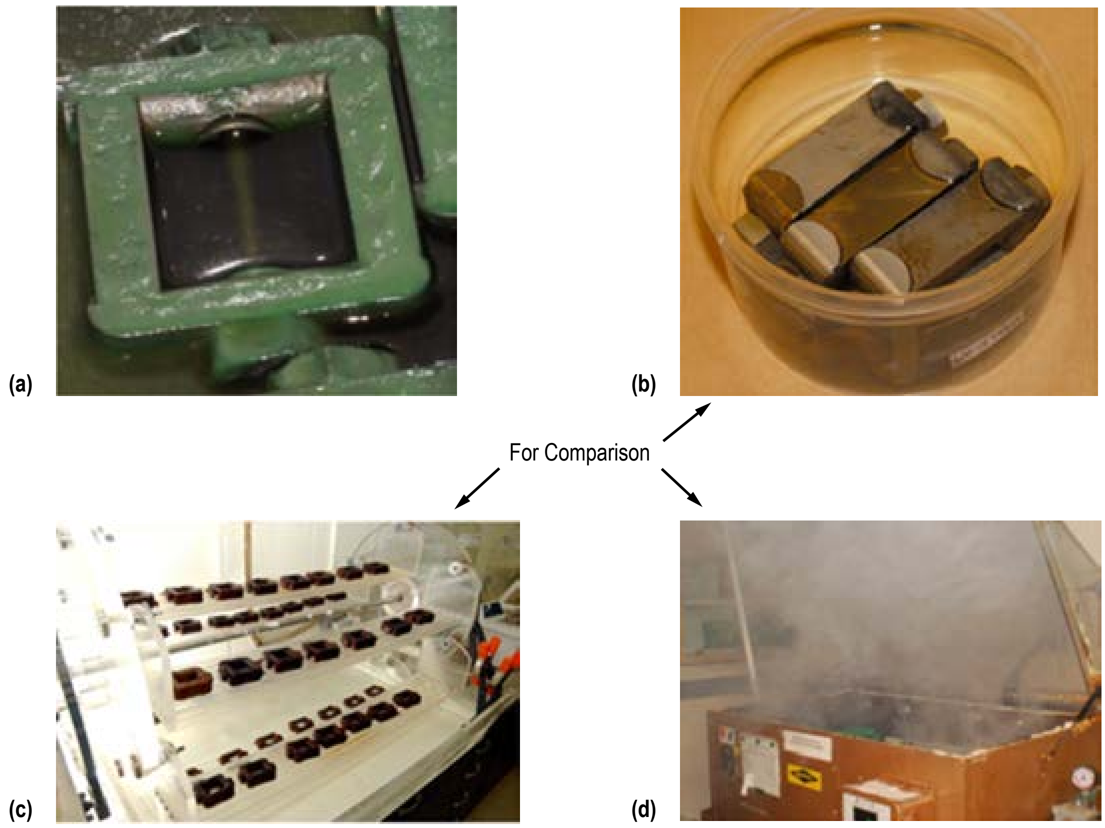


Figure 4. Testing methods: (a) Total immersion in the ECLSS fluids to determine acceptability, (b) total immersion in DI water, (c) 3.5% NaCl alternate immersion tester (not the actual specimens—for illustrative purpose only), and (d) 5% salt spray chamber.

4. RESULTS AND DISCUSSION

The stress corrosion results are presented in table 4. As shown in the table, no failures occurred in the pretreat, brine, or any of the supplementary tests performed. The maximum length of exposure for the materials evaluated was 1 year.

The Cronidur 30 specimens that survived 313 days of exposure to 3.5% NaCl alternate immersion, salt spray, and high humidity at 25 ksi (10% YS) stress level (last three rows in table 4) were unloaded and reloaded to a higher stress, as shown in table 5.

The Cronidur 30 specimens were not stressed initially to high percentages of the yield strength because this material, as hard as it was tested, was expected to show some susceptibility to stress corrosion. Surprisingly, they did not fail, even after increasing the stress as seen in table 5.

Appearance of the specimens before and during exposure is presented in figures 5 through 10. Note that Cronidur 30 specimens are not shown in figure 9 as they were removed from test at a later date.

At the end of the exposures, the specimens were cleaned and unloaded. Representative specimens were subjected to metallography and the results are presented in figures 11 through 16. As seen, metallography did not indicate any corrosion or stress corrosion attack on the materials.

The remaining stress corrosion specimens were tensile tested to determine any reduction in tensile strength and the results are presented in table 6. Detailed postexposure tensile tests data are presented in appendix D. Appendix D also shows initial average tensile data for comparison, as well as the stress corrosion test conditions.

Inconel 625, Hastelloy C276, TiCP, Ti-6-4, and Ti-6-4 ELI did not experience reduction in tensile strength. One Cronidur 30 specimen out of 10 exposed to pretreat experienced an 8% reduction in tensile strength (specimen No. C30-4). That sample was originally stressed to 50 ksi (20% of YS). Three of 10 specimens exposed to brine experienced reduction in tensile strength: (1) Specimen C30-19, 40% reduction (originally stressed to 25 ksi (10% YS)), (2) specimen C30-20, 42% reduction (originally stressed to 15 ksi (6% YS)), and (3) specimen C30-23, 16% reduction (tested with no applied stress). Of the six alloys tested, Cronidur 30 has the highest tensile strength (300.4 ksi) and hardness (HRC 58), and it was expected to be more susceptible than the rest of the materials tested. It must be mentioned that this material is expected to be used in bearing applications in the water recovery system. For this application, the material will be mostly in compression.

Table 4. Stress corrosion test results in various environments.

Alloy	Test Environment	Stress Level (% YS)	Stress Level (ksi)	Failure Ratio	Days to Fail
Inconel 625	Pretreat	75	58.3	0/3	NF in 365 days
		0	0	0/1	NF in 365 days
	Brine	75	58.3	0/3	NF in 365 days
		0	0	0/1	NF in 365 days
	DI water	75	58.3	0/1	NF in 316 days
Hastelloy C276	Pretreat	75	50.3	0/3	NF in 365 days
		0	0	0/1	NF in 365 days
	Brine	75	50.3	0/3	NF in 365 days
		0	0	0/1	NF in 365 days
	DI water	75	50.3	0/1	NF in 316 days
TiCP	Pretreat	75	68.6	0/3	NF in 365 days
		0	0	0/1	NF in 365 days
	Brine	75	68.6	0/3	NF in 365 days
		0	0	0/1	NF in 365 days
	DI water	75	68.6	0/1	NF in 316 days
Ti-6-4	Pretreat	75	103.9	0/3	NF in 365 days
		0	0	0/1	NF in 365 days
	Brine	75	103.9	0/3	NF in 365 days
		0	0	0/1	NF in 365 days
	DI water	75	103.9	0/1	NF in 316 days
Ti-6-4 ELI	Pretreat	75	104.0	0/3	NF in 365 days
		0	0	0/1	NF in 365 days
	Brine	75	104.0	0/3	NF in 365 days
		0	0	0/1	NF in 365 days
	DI water	75	104.0	0/1	NF in 316 days
Cronidur 30 (hardened, HRC 58 or higher)	Pretreat	6	15.0	0/3	NF in 341 days
		10	25.0	0/3	NF in 341 days
		20	50.0	0/3	NF in 341 days
		0	0	0/1	NF in 341 days
	Brine	6	15.0	0/3	NF in 341 days
		10	25.0	0/3	NF in 341 days
		20	50.0	0/3	NF in 341 days
		0	0	0/1	NF in 341 days
	DI water	10	25.0	0/1	NF in 316 days
	5% salt spray	10	25.0	0/3	NF in 313 days
	High humidity	10	25.0	0/3	NF in 313 days
	3.5% NaCl AI	10	25.0	0/3	NF in 313 days

*NF = no failures

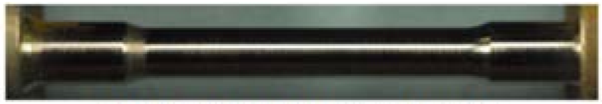
Table 5. Supplementary SCC test results for hardened Cronidur 30 steel in mixed environments and residual tensile strength.

Specimen No.	Initially Tested at 25 ksi in the Environments Shown Below Without Failing	Removed, Unloaded, Reloaded, and Subjected to the Following Environment	Stress Level for the Final Exposure (% YS)	Stress Level for the Final Exposure (ksi)	Result	Residual Tensile Strength (UTS_f) (ksi)	UTS_f / UTS_i*
C30-24	5% salt spray at 95 ºF for 313 days	3.5% NaCl alternate immersion for 46 days	20	50	Survived 359 days total exposure	304.9	1.01
C30-25	5% salt spray at 95 ºF for 313 days	3.5% NaCl alternate immersion for 46 days	20	50	Survived 359 days total exposure	298.6	0.99
C30-26	5% salt spray at 95 ºF for 313 days	3.5% NaCl alternate immersion for 46 days	30	75	Survived 359 days total exposure	308.5	1.03
C30-27	High humidity at 95 ºF for 313 days	3.5% NaCl alternate immersion for 46 days	30	75	Survived 359 days total exposure	299.7	1.00
C30-28	High humidity at 95 ºF for 313 days	3.5% NaCl alternate immersion for 46 days	40	100	Survived 359 days total exposure	319.7	1.06
C30-29	High humidity at 95 ºF for 313 days	3.5% NaCl alternate immersion for 46 days	40	100	Survived 359 days total exposure	290.8	0.97
C30-30	3.5% NaCl alternate immersion for 313 days	3.5% NaCl alternate immersion for 46 days	50	126	Survived 359 days total exposure	303.6	1.01
C30-31	3.5% NaCl alternate immersion for 313 days	3.5% NaCl alternate immersion for 46 days	50	126	Survived 359 days total exposure	295.3	0.98
C30-32	3.5% NaCl alternate immersion for 313 days	3.5% NaCl alternate immersion for 46 days	66	166	Survived 359 days total exposure	287.5	0.96

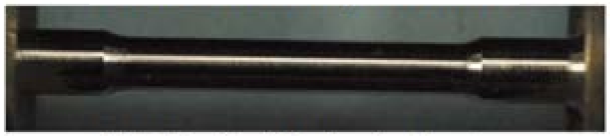
*UTS_i = 300.4 ksi (averaged initial ultimate tensile strength obtained from nonexposed specimens).

Figure 5. Representative specimens before and during exposure to pretreat.

Figure 6. Representative specimens before and during exposure to brine.

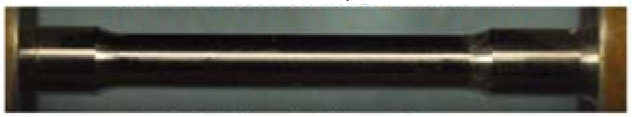


625-12 After 114 Days in DI Water

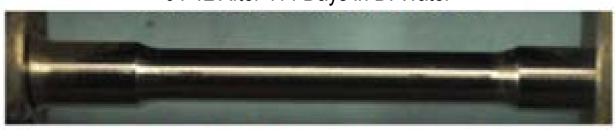


276-12 After 114 Days in DI Water

TiCP-12 After 114 Days in DI Water



64-12 After 114 Days in DI Water



ELI-12 After 114 Days in DI Water

C30-33 After 114 Days in DI Water

Figure 7. Representative specimens during exposure to DI water.

Figure 8. Specimens after exposure to pretreat for 365 days.

Figure 9. Specimens after exposure to brine for 365 days.

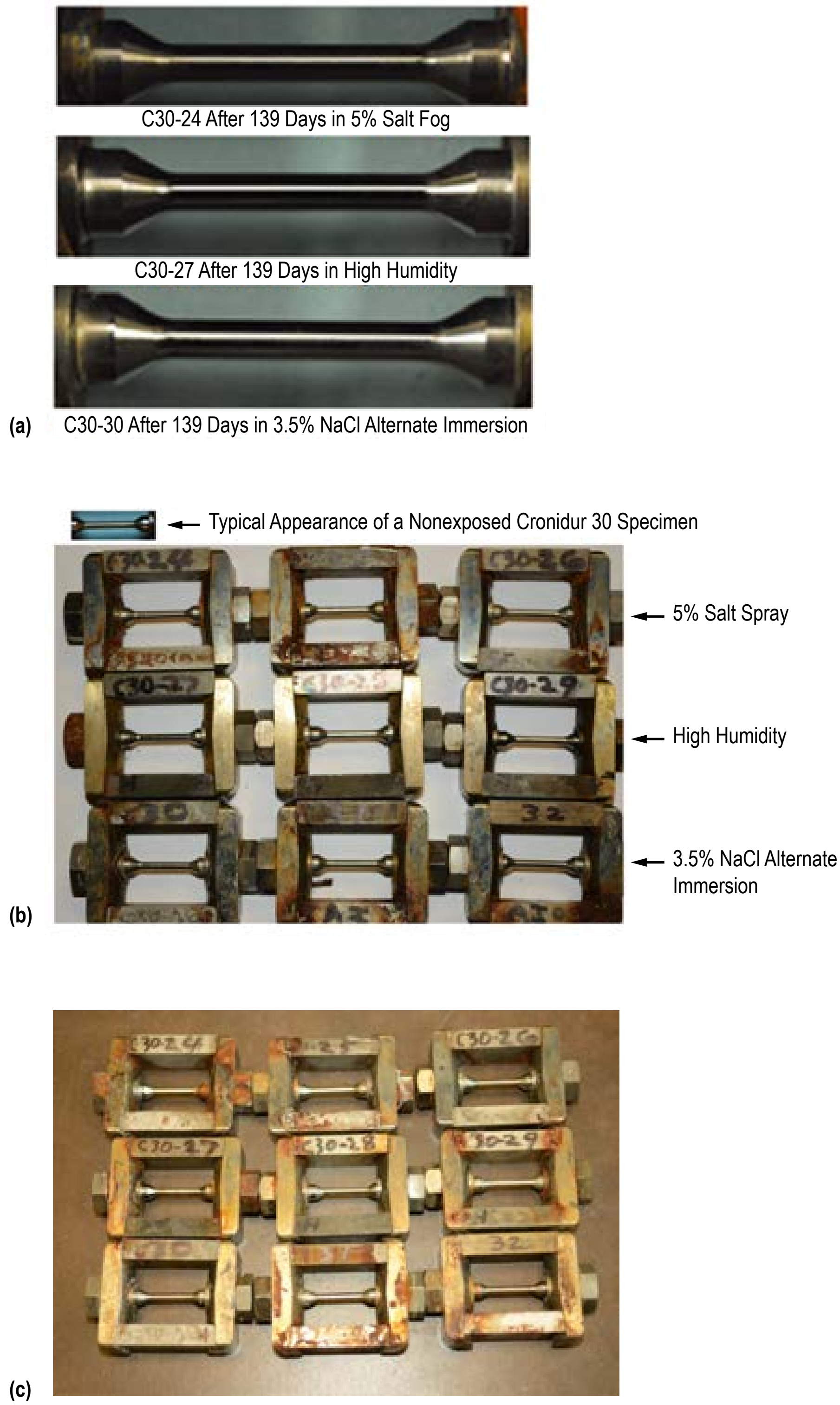
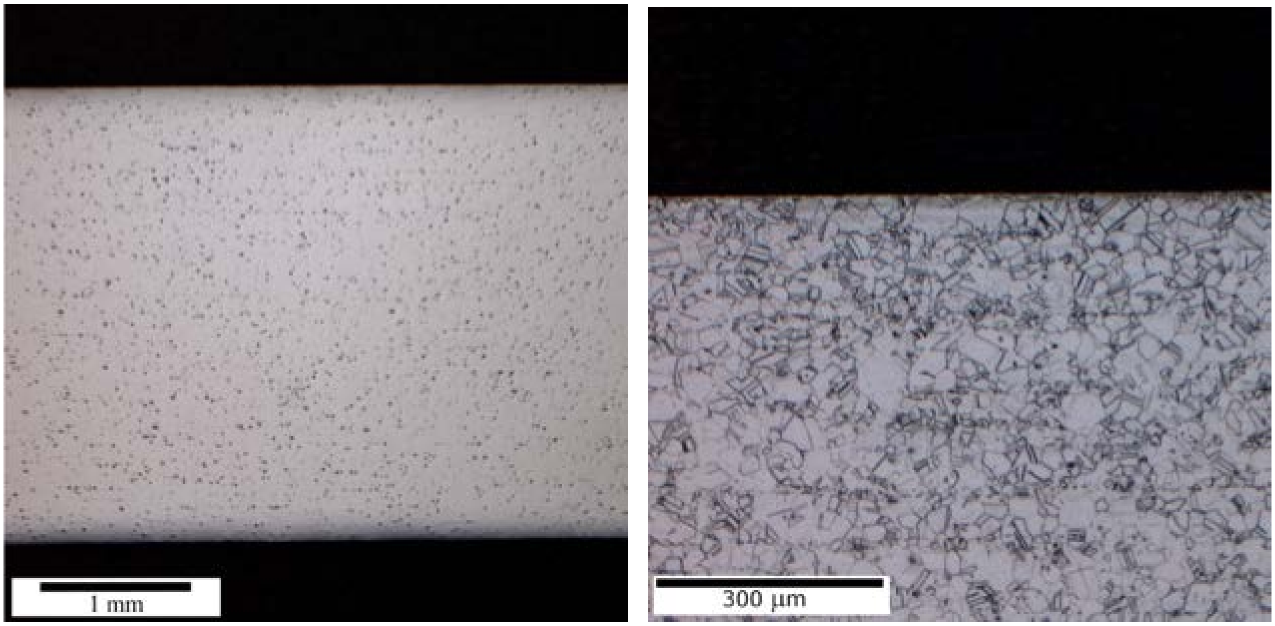
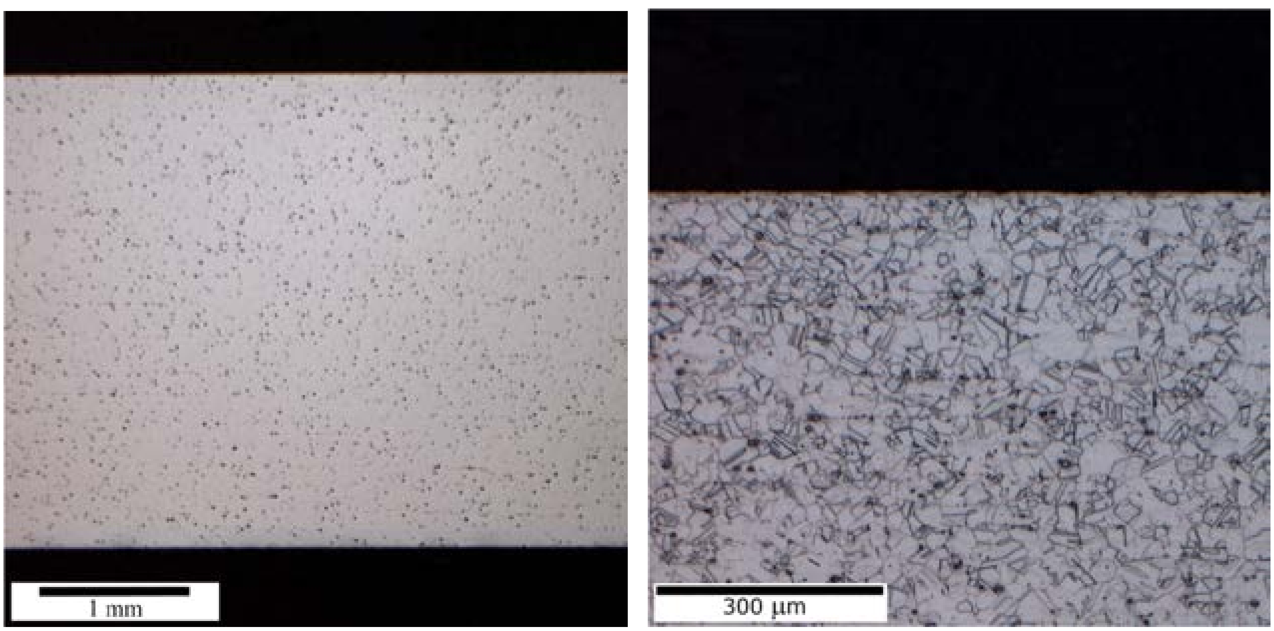


Figure 10. Cronidur 30 specimens during and after exposure to various complementary environments: (a) C30-24, C30-27, and C30-30 after 139 days in various environments, (b) after 313 days of exposure to various environments, and (c) 359-day exposure described in table 5.

(a)


× 20 Magnification, Unetched

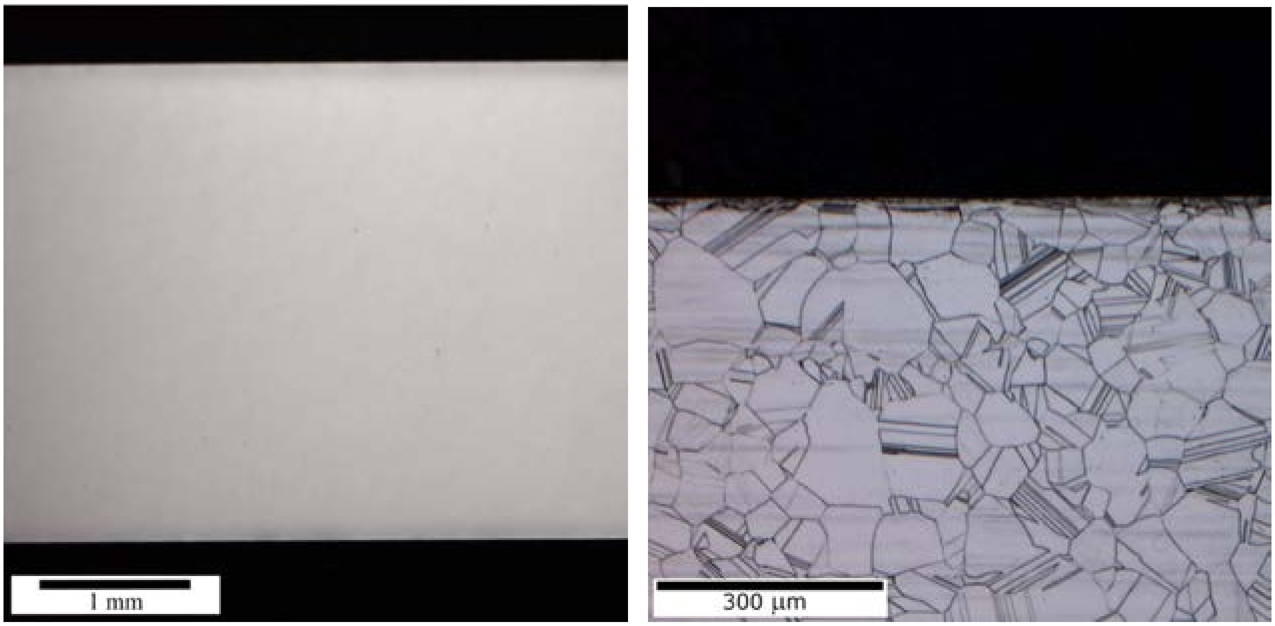
× 100 Magnification, Etched
(15 mL HCl, 10 mL Acetic Acid, 10 mL HNO_3)

(b)


× 20 Magnification, Unetched

× 100 Magnification, Etched
(15 mL HCl, 10 mL Acetic Acid, 10 mL HNO_3)

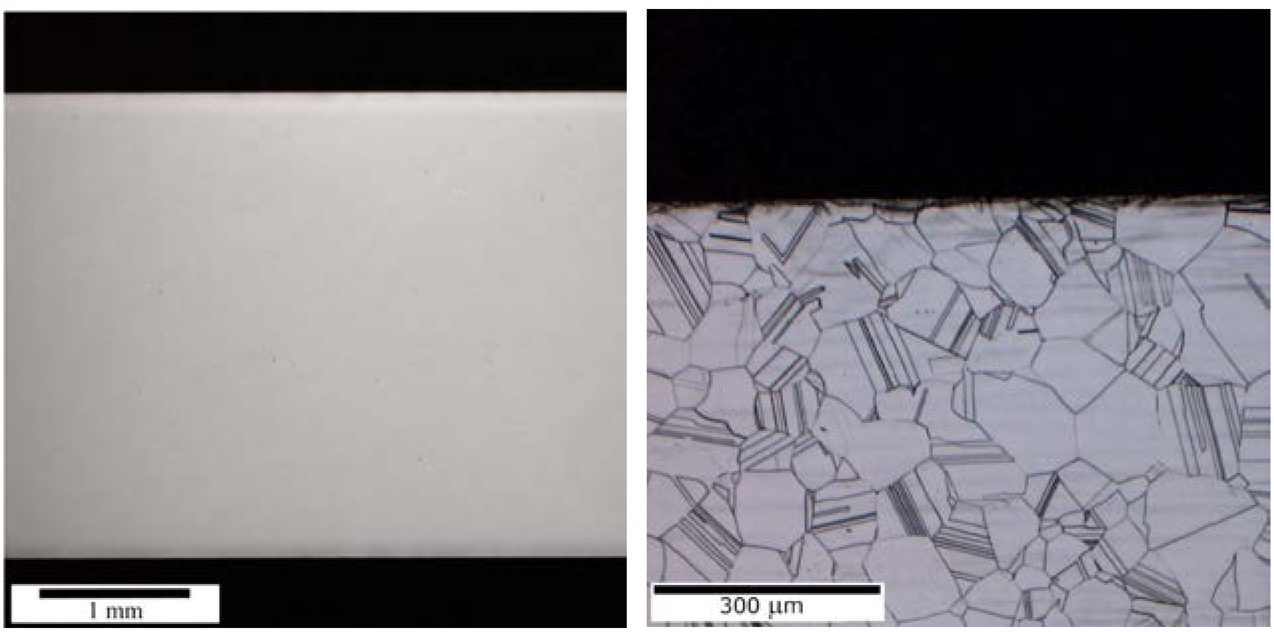
Figure 11. Photomicrographs of Inconel 625 initially stressed to 75% YS (58.3 ksi) and exposed for 365 days in (a) pretreat (sample 625-6) and (b) brine (sample 625-10).



(a)

× 20 Magnification, Unetched

× 100 Magnification, Etched
(30 mL HCl, 5 mL HF, 10 mL HNO_3)

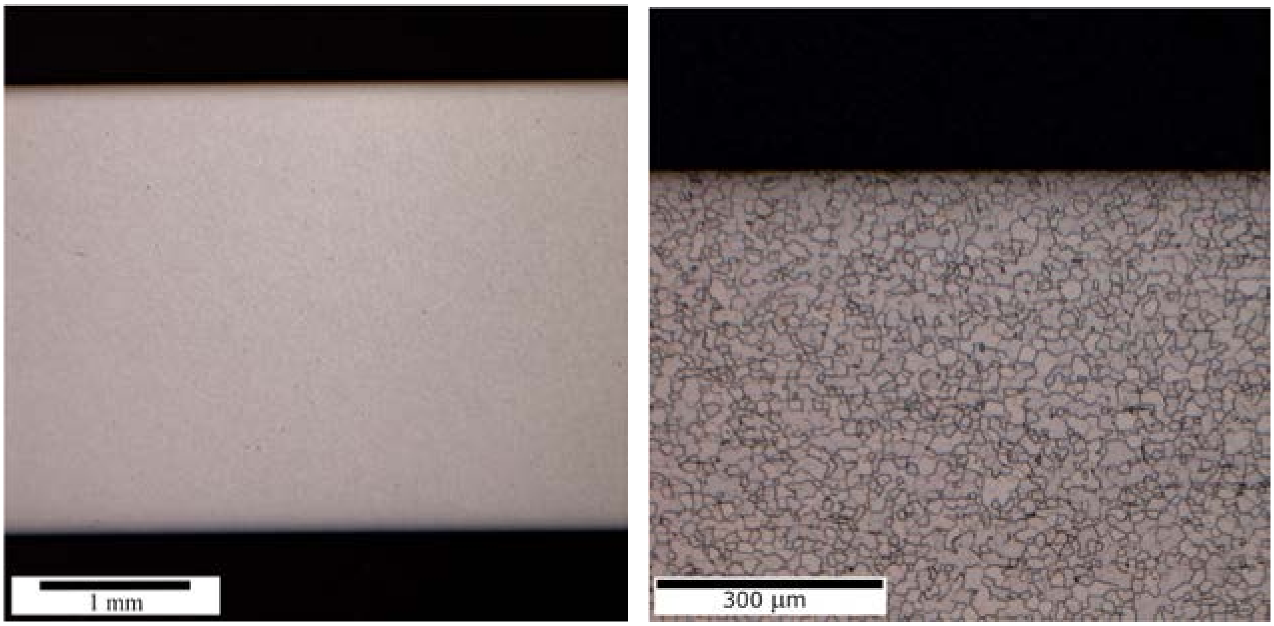


(b)

× 20 Magnification, Unetched

× 100 Magnification, Etched
(30 mL HCl, 5 mL HF, 10 mL HNO_3)

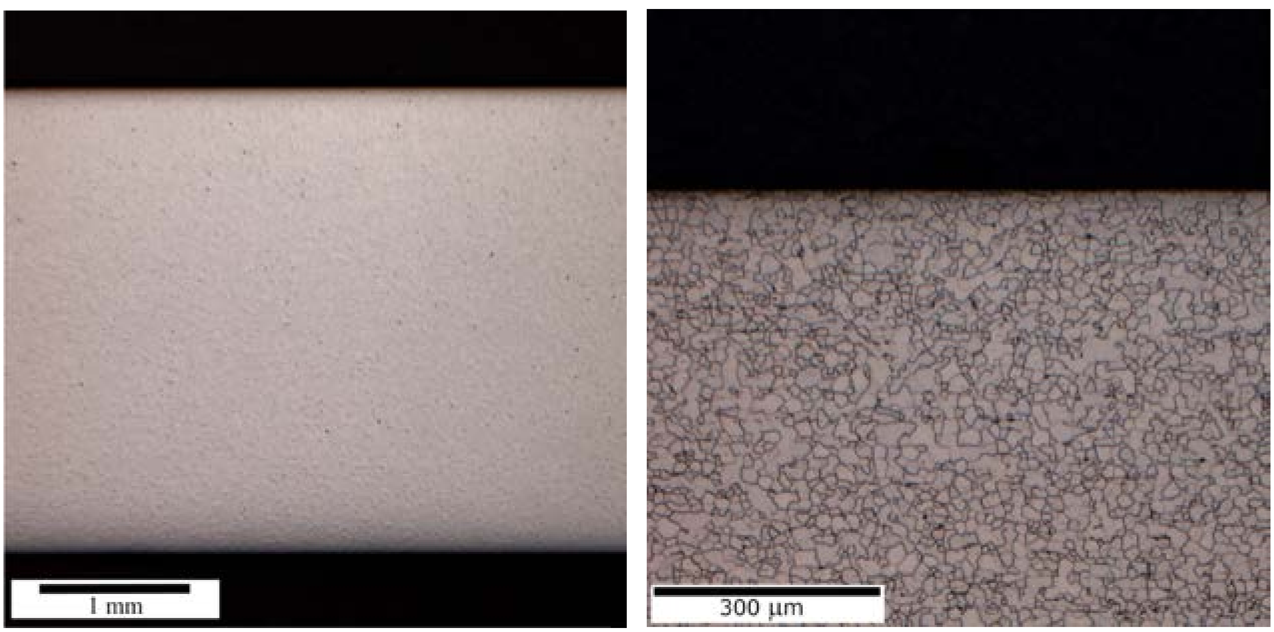
Figure 12. Photomicrographs of Hastelloy C276 initially stressed to 75% YS (50.3 ksi) and exposed for 365 days in (a) pretreat (sample C276-6) and (b) brine (sample C276-10).



(a)

× 20 Magnification, Unetched

× 100 Magnification, Etched (Kroll's Reagent)



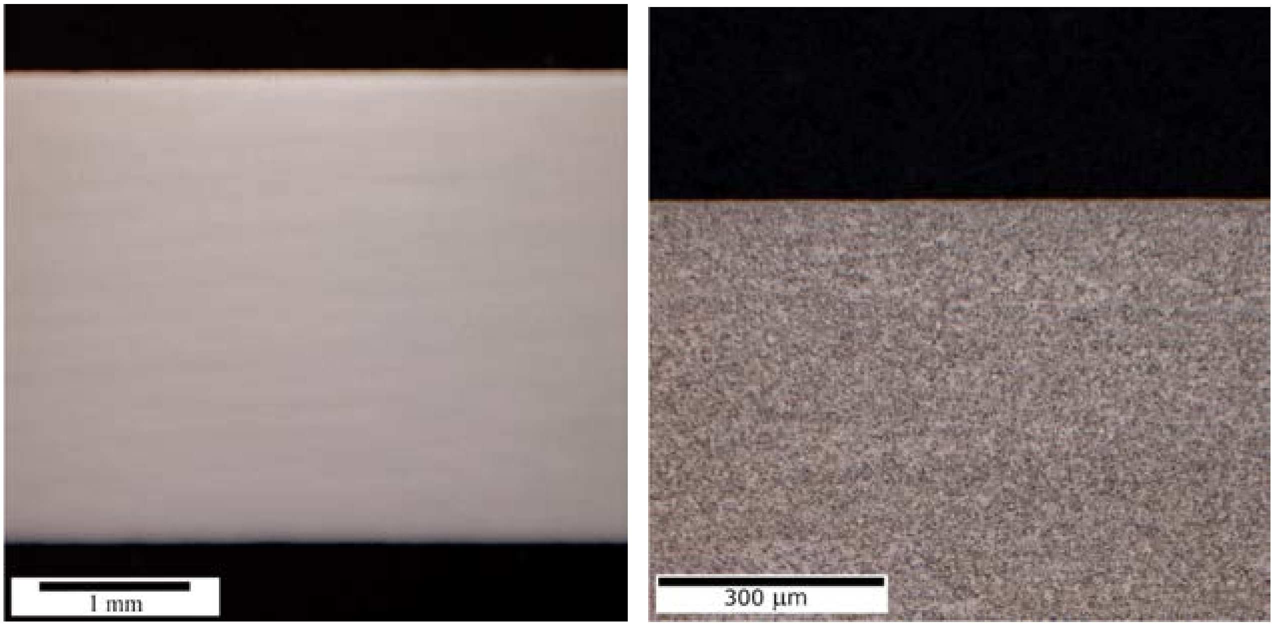
(b)

× 20 Magnification, Unetched

× 100 Magnification, Etched (Kroll's Reagent)

Figure 13. Photomicrographs of TiCP initially stressed to 75% YS (68.6 ksi) and exposed for 365 days in (a) pretreat (sample TiCP-6) and (b) brine (sample TiCP-10).

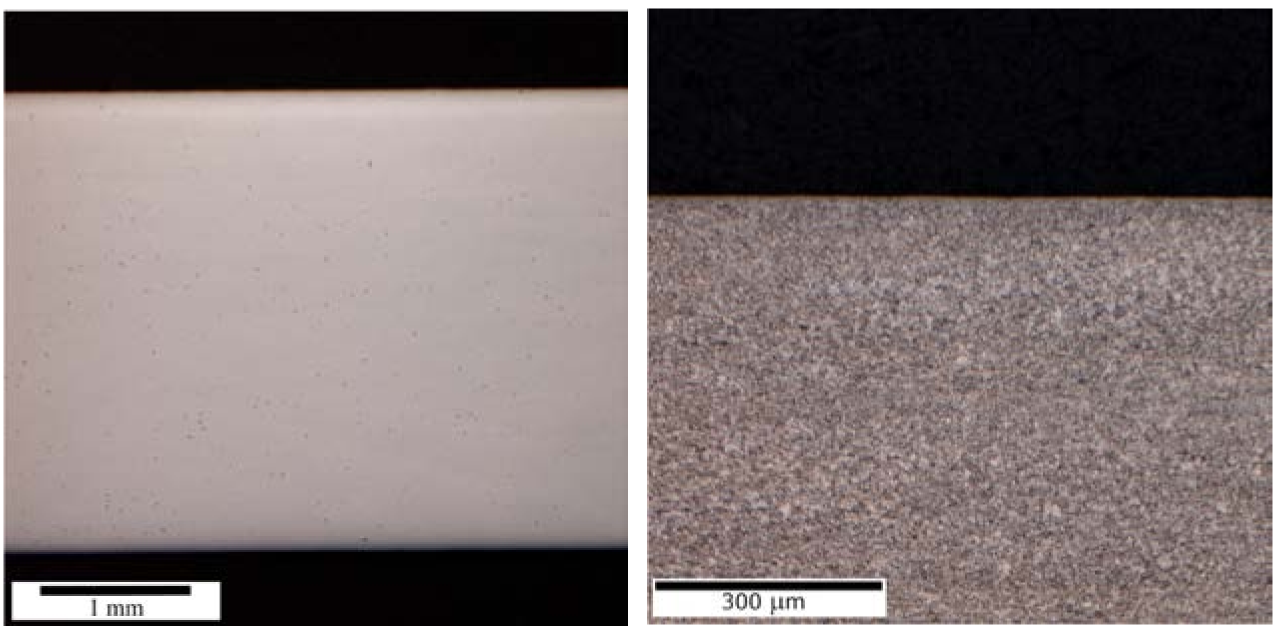
(a)



× 20 Magnification, Unetched

× 100 Magnification, Etched (Kroll's Reagent)

(b)



× 20 Magnification, Unetched

× 100 Magnification, Etched (Kroll's Reagent)

Figure 14. Photomicrographs of Ti-6A-4V initially stressed to 75% YS (103.9 ksi) and exposed for 365 days in (a) pretreat (sample Ti-64-6) and (b) brine (sample Ti-64-10).

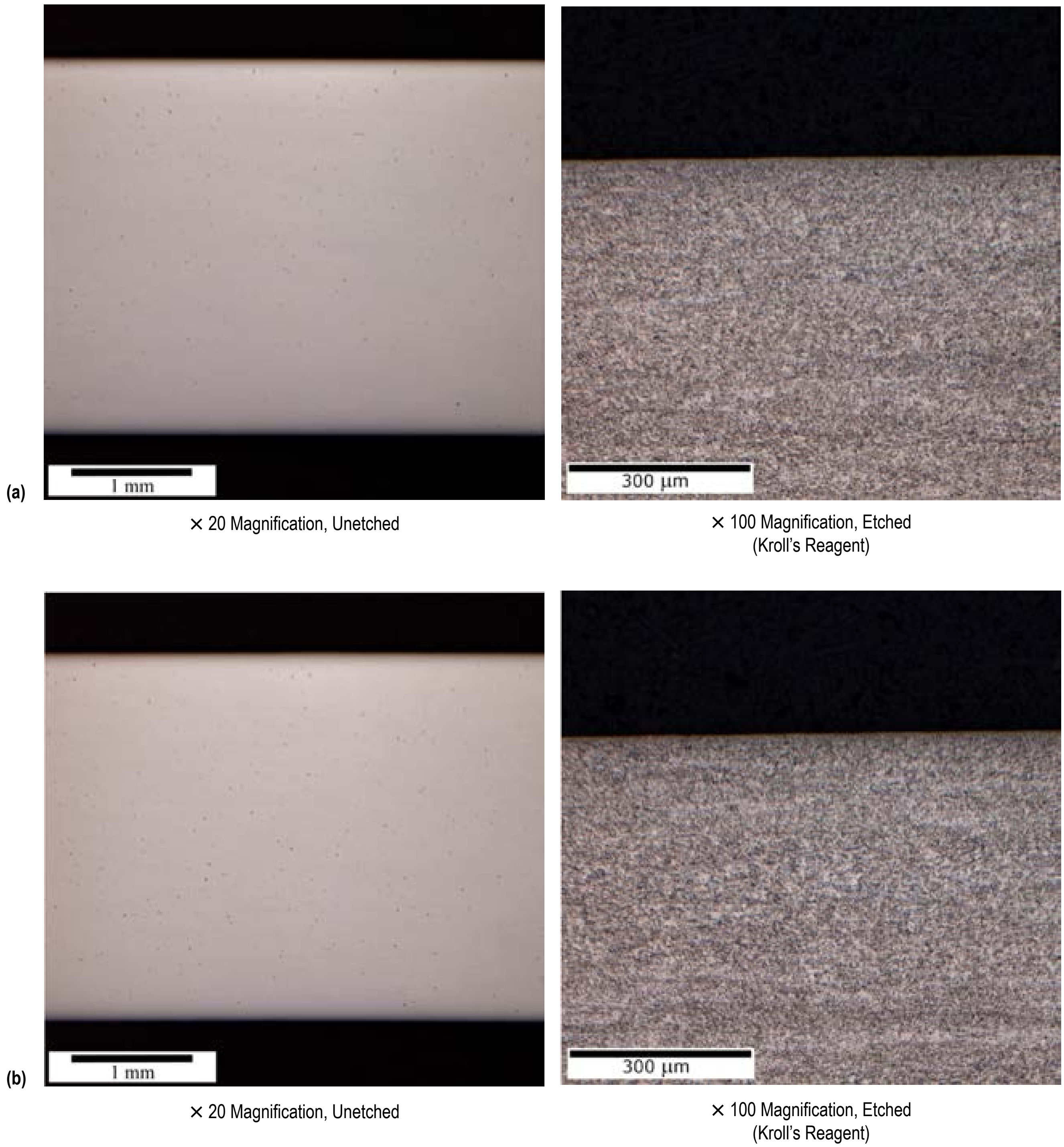
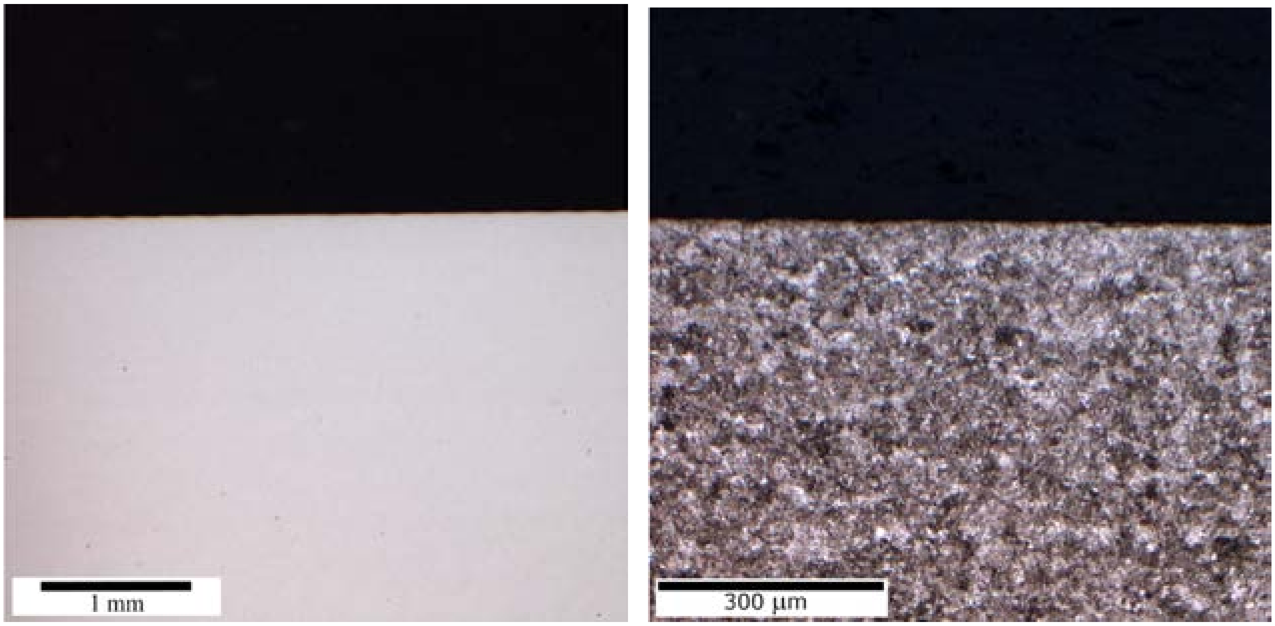


Figure 15. Photomicrographs of Ti-6-4 ELI initially stressed to 75% YS (104 ksi) and exposed for 365 days in (a) pretreat (sample ELI-6) and (b) brine (sample ELI-10).

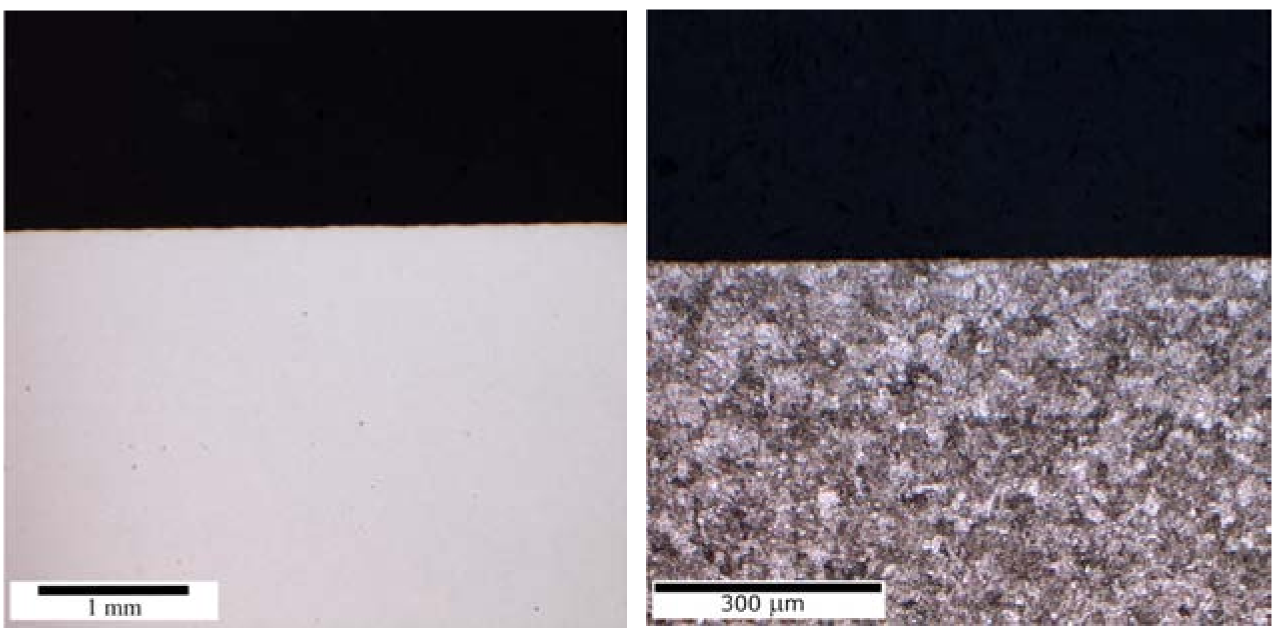
(a)



× 20 Magnification, Unetched

× 100 Magnification, Etched (Kalling's Reagent)

(b)



× 20 Magnification, Unetched

× 100 Magnification, Etched (Kalling's Reagent)

Figure 16. Photomicrographs of Cronidur 30 initially stressed to 20% YS (50 ksi) and exposed for 341 days in (a) pretreat (sample C30-6) and (b) brine (sample C30-16).

Table 6. Posttest evaluation for metals exposed to phosphoric acid-based ECLSS pretreat, brine, and DI water.

Specimen No.[1]	Alloy	Test Environment	Stress Level (% YS)	Stress Level (ksi)	Test Duration	UTS_i[2] (ksi)	UTS_f[3] (ksi)	UTS_f/UTS_i	Evaluation Performed
625-4	In 625	Pretreat	75	58.3	365	136.0	134.8	0.99	Tensile
625-5	In 625	Pretreat	75	58.3	365	136.0	137.6	1.01	Tensile
625-6	In 625	Pretreat	75	58.3	365	136.0	–	–	Metall.
625-7	In 625	Pretreat	0	0	365	136.0	137.2	1.01	Tensile
625-8	In 625	Brine	75	58.3	365	136.0	135.9	1.00	Tensile
625-9	In 625	Brine	75	58.3	365	136.0	137.3	1.01	Tensile
625-10	In 625	Brine	75	58.3	365	136.0	–	–	Metall.
625-11	In 625	Brine	0	0	365	136.0	136.0	1.00	Tensile
625-12	In 625	DI water	75	58.3	316	136.0	137.4	1.01	Tensile
276-4	C276	Pretreat	75	50.3	365	120.7	122.5	1.01	Tensile
276-5	C276	Pretreat	75	50.3	365	120.7	123.1	1.02	Tensile
276-6	C276	Pretreat	75	50.3	365	120.7	–	–	Metall.
276-7	C276	Pretreat	0	0	365	120.7	122.0	1.01	Tensile
276-8	C276	Brine	75	50.3	365	120.7	120.0	0.99	Tensile
276-9	C276	Brine	75	50.3	365	120.7	122.4	1.01	Tensile
276-10	C276	Brine	75	50.3	365	120.7	–	–	Metall.
276-11	C276	Brine	0	0	365	120.7	123.6	1.02	Tensile
276-12	C276	DI water	75	50.3	316	120.7	123.4	1.02	Tensile
TiCP-4	TiCP	Pretreat	75	68.6	365	110.9	114.2	1.03	Tensile
TiCP-5	TiCP	Pretreat	75	68.6	365	110.9	112.8	1.02	Tensile
TiCP-6	TiCP	Pretreat	75	68.6	365	110.9	–	–	Metall.
TiCP-7	TiCP	Pretreat	0	0	365	110.9	112.8	1.02	Tensile
TiCP-8	TiCP	Brine	75	68.6	365	110.9	112.4	1.01	Tensile
TiCP-9	TiCP	Brine	75	68.6	365	110.9	111.9	1.01	Tensile
TiCP-10	TiCP	Brine	75	68.6	365	110.9	–	–	Metall.
TiCP-11	TiCP	Brine	0	0	365	110.9	111.7	1.01	Tensile
TiCP-12	TiCP	DI water	75	68.6	316	110.9	114.6	1.03	Tensile
Ti-64-4	Ti-6-4	Pretreat	75	103.9	365	156.3	159.5	1.02	Tensile
Ti-64-5	Ti-6-4	Pretreat	75	103.9	365	156.3	157.8	1.01	Tensile
Ti-64-6	Ti-6-4	Pretreat	75	103.9	365	156.3	–	–	Metall.
Ti-64-7	Ti-6-4	Pretreat	0	0	365	156.3	158.2	1.01	Tensile
Ti-64-8	Ti-6-4	Brine	75	103.9	365	156.3	157.1	1.01	Tensile
Ti-64-9	Ti-6-4	Brine	75	103.9	365	156.3	154.5	0.99	Tensile
Ti-64-10	Ti-6-4	Brine	75	103.9	365	156.3	–	–	Metall.
Ti-64-11	Ti-6-4	Brine	0	0	365	156.3	156.7	1.00	Tensile
Ti-64-12	Ti-6-4	DI water	75	103.9	316	156.3	159.9	1.02	Tensile
ELI-4	Ti-6-4 ELI	Pretreat	75	104.0	365	157.2	161.7	1.03	Tensile
ELI-5	Ti-6-4 ELI	Pretreat	75	104.0	365	157.2	162.2	1.03	Tensile
ELI-6	Ti-6-4 ELI	Pretreat	75	104.0	365	157.2	–	–	Metall.
ELI-7	Ti-6-4 ELI	Pretreat	0	0	365	157.2	163.5	1.04	Tensile
ELI-8	Ti-6-4 ELI	Brine	75	104.0	365	157.2	163.6	1.04	Tensile
ELI-9	Ti-6-4 ELI	Brine	75	104.0	365	157.2	162.6	1.03	Tensile

Table 6. Posttest evaluation for metals exposed to phosphoric acid-based ECLSS pretreat, brine, and DI water (Continued).

Specimen No.(1)	Alloy	Test Environment	Stress Level (% YS)	Stress Level (ksi)	Test Duration	UTS_i(2) (ksi)	UTS_f(3) (ksi)	UTS_f/UTS_i	Evaluation Performed
ELI-10	Ti-6-4 ELI	Brine	75	104.0	365	157.2	–	–	Metall.
ELI-11	Ti-6-4 ELI	Brine	0	0	365	157.2	161.7	1.03	Tensile
ELI-12	Ti-6-4 ELI	DI Water	75	104.0	316	157.2	162.7	1.03	Tensile
C30-4	Cronid. 30	Pretreat	20	50.0	341	300.4	277.1	0.92	Tensile
C30-5	Cronid. 30	Pretreat	20	50.0	341	300.4	295.5	0.98	Tensile
C30-6	Cronid. 30	Pretreat	20	50.0	341	300.4	–	–	Metall.
C30-7	Cronid. 30	Pretreat	10	25.0	341	300.4	306.2	1.02	Tensile
C30-8	Cronid. 30	Pretreat	10	25.0	341	300.4	305.7	1.02	Tensile
C30-9	Cronid. 30	Pretreat	10	25.0	341	300.4	320.4	1.07	Tensile
C30-10	Cronid. 30	Pretreat	6	15.0	341	300.4	314.1	1.05	Tensile
C30-11	Cronid. 30	Pretreat	6	15.0	341	300.4	314.8	1.05	Tensile
C30-12	Cronid. 30	Pretreat	6	15.0	341	300.4	295.9	0.99	Tensile
C30-13	Cronid. 30	Pretreat	0	0	341	300.4	294.1	0.98	Tensile
C30-14	Cronid. 30	Brine	20	50.0	341	300.4	302.7	1.01	Tensile
C30-15	Cronid. 30	Brine	20	50.0	341	300.4	309.7	1.04	Tensile
C30-16	Cronid. 30	Brine	20	50.0	341	300.4	–	–	Metall.
C30-17	Cronid. 30	Brine	10	25.0	341	300.4	308.7	1.03	Tensile
C30-18	Cronid. 30	Brine	10	25.0	341	300.4	300.9	1.00	Tensile
C30-19	Cronid. 30	Brine	10	25.0	341	300.4	179.9	0.60	Tensile
C30-20	Cronid. 30	Brine	6	15.0	341	300.4	174.1	0.58	Tensile
C30-21	Cronid. 30	Brine	6	15.0	341	300.4	295.0	0.98	Tensile
C30-22	Cronid. 30	Brine	6	15.0	341	300.4	288.5	0.96	Tensile
C30-23	Cronid. 30	Brine	0	0	341	300.4	251.6	0.84	Tensile
C30-33	Cronid. 30	DI Water	10	25.0	316	300.4	312.8	1.04	Tensile

(1) Samples 1–3 of each metal were used for obtaining initial tensile data without exposure.
(2) UTS_i = initial average ultimate tensile strength of nonexposed specimens.
(3) UTS_f = final ultimate tensile strength of exposed specimens.

Representative samples that were tensile tested are shown in figure 17. A neck-down effect (localized area reduction of the specimen during plastic deformation) can be observed for all the specimens except for Cronidur 30. That can be explained by the low ductility of this material when it is in the hard condition.

The stress corrosion specimens that were exposed to mixed environments were also tensile tested and the final strength compared with the initial strength. Those results are presented in the last two columns of table 5. The ratio of final-to-average initial strength values ranged from 0.96 to 1.06, and the average value was 1. These results are significantly better than expected for this material in NaCl and high humidity environments.

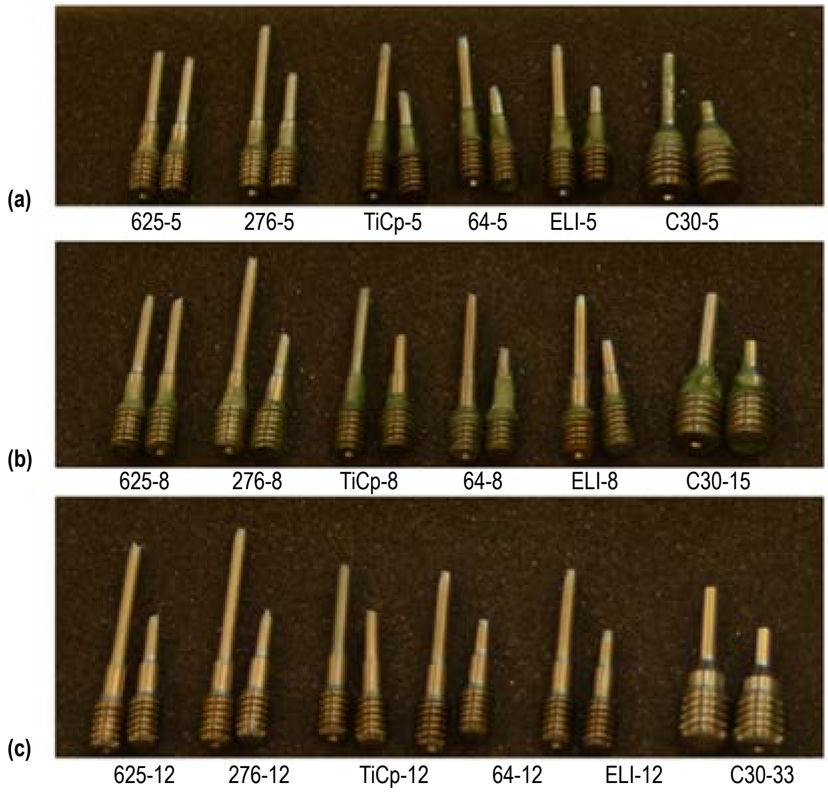


Figure 17. Stress corrosion specimens exposed to (a) phosphoric acid-based pretreat, (b) brine, and (c) DI water without failing and subsequently tensile tested. Specimens shown were exposed for 365 days, except Cronidur 30 specimens, which were exposed for 341 days.

5. CONCLUSIONS

All the stress corrosion specimens exposed to the phosphoric acid-based ECLSS pretreat and brine solutions survived exposures of up to 1 year. Therefore, they passed the first stage of this evaluation, consisting of exposing the samples to the fluids under a sustained tensile stress.

The following stage consisted of performing posttest evaluations that included metallography to examine the microstructure and tensile tests to determine residual strength. Inconel 625, Hastelloy C276, TiCP, Ti-6-4, and Ti-6-4 ELI did not show corrosion or stress corrosion cracks in the metallographic analysis and did not experience reduction in tensile strength as a result of the exposure to the ECLSS fluids. Therefore, these alloys, as tested, can be considered resistant to stress corrosion and corrosion in the brine and pretreat.

Cronidur 30 steel exposed to the ECLSS fluids did not show corrosion or stress corrosion cracks in the metallographic analysis, but several specimens suffered reductions in the tensile strength. That reduction was moderate in the pretreat (1 specimen out of 10 suffered an 8% reduction) and significant in brine (3 specimens out of 10 suffered reductions of 16%, 40%, and 42%). Even when reductions in strength were found, the results are still better than expected for this high-hardness (HRC >58), high-strength (300.4 ksi UTS) material. This material could be used successfully under compression, such as for bearings; however, sustained tensile stresses on this material should be avoided, or at least maintain them as low as possible.

Supplementary tests performed on Cronidur 30 in mixed environments of high humidity, salt spray, and salt water alternate immersion did not produce any failures, and tensile test results after exposure were also acceptable.

APPENDIX A—MATERIALS CERTIFICATIONS

Materials certifications are shown for Inconel 625 (fig. 18), Hastelloy C276 (fig. 19), TiCP (fig. 20), Ti-6-4 (fig. 21), Ti-6-4 ELI (fig. 22), and Cronidur 30 (fig. 23).

CERTIFICATE OF TESTS   ABNAHMEPRUEFZEUGNIS   CERTIFICAT DE CONTROLE
CERT SERIAL# 000756584

CARPENTER
Carpenter Technology Corporation
101 West Bern Street, Reading, Pa. 19601
Tel. (610) 208-2000 (800) 338-4592

- THE RECORDING OF FALSE, FICTITIOUS OR FRAUDULENT STATEMENTS OR ENTRIES ON THIS DOCUMENT MAY BE PUNISHED AS A FELONY UNDER FEDERAL STATUTES INCLUDING FEDERAL LAW, TITLE 18, CHAPTER 47.
- THE VALUES AND OTHER TECHNICAL DATA [illegible] THE RESULTS OF ANALYSES AND TESTS MADE ON SAMPLES COLLECTED FROM THE TOTAL [illegible] ORIGINAL [illegible] RECORDS CAN BE TRACED BY REFERENCE TO THE CARPENTER ORDER NUMBER.
- MATERIAL IS MANUFACTURED FREE FROM MERCURY, RADIUM, ALPHA AND GAMMA SOURCE CONTAMINATION.
- THIS DOCUMENT SHALL NOT BE REPRODUCED, EXCEPT IN FULL, WITHOUT THE WRITTEN CONSENT OF CARPENTER TECHNOLOGY CORPORATION.

600213-4

12/29/10
CUSTOMER/BESTELLER/CLIENT   SELLER/VERKÄUFER/VENDEUR   PAGE 1 OF 1

L. MILLER & SON, INC.
LMS METAL SALES
606 TRIANA BLVD.
HUNTSVILLE, AL 35805

RAN

CUSTOMER ORDER NO. / BESTELL NR. / N° DE COMMANDE	CARPENTER NO. / WERKS NR. / N° DE REFERENCE INTERNE	DATE / DATUM / DATE	WEIGHT / GEWICHT / POIDS
46209-6 S# 19680	W78565	12/29/10	2052.000

HEAT NUMBER/SCHMELZEN-NR./N° DE COULEE: 600213

PRODUCT DESCRIPTION: PYROMET 625 HI TEMP ALLOY ANNEALED GROUND

SPECIFICATION: AMS 5666 REV F (05/ /06)
ASTM-B446-03(2008) GRADE 1
GE S-1000 (03/02/10)
DFARS 1998 EDITION
GE S-400 (10/10/08)

SIZE 0.375000 IN. (9.53 MM) RD BAR   INGOT 4

PRIMARY HEAT CHEMISTRY(WT%): (TEST METHOD IS SHOWN IN PARENTHESIS)

C (COM)	MN(XRF)	SI(XRF)	P (OES)	S (COM)	CR(XRF)
0.04	0.06	0.09	0.004	LT .001	22.34
NI(XRF)	MO(XRF)	CO(XRF)	AL(OES)	TI(XRF)	CB(XRF)
60.69	8.81	0.06	0.15	0.28	3.58
TA(OES)	CB+TA	FE(XRF)			
0.01	3.59	3.78			

GEAG SUPPLIER CODE - 21100/CARPENTER
HARDNESS AS SHIPPED 279HB (29HRC)

YIELD STRENGTH, (0.20 %) KSI(MPA) 105.0(724)
TENSILE STRENGTH, KSI(MPA) 138.0(951)
ELONGATION IN 1.54", % 51.0

GRAIN SIZE PER ASTM E112: 9
5 ML H2O2(30%), 100 ML HCL

MATERIAL PRODUCED ON THIS ORDER WAS MELTED AND MANUFACTURED IN THE U.S.A. MATERIAL HAS BEEN MELTED IN USA OR QUALIFYING COUNTRY TO DFARS REQUIREMENTS 252.225-7014 WITH ALTERNATE 1 FOR QUALIFYING COUNTRY 225.872.1, SUPERSEDED BY DFARS REQUIREMENTS DFARS 252.225-7008 AND 252.225-7009. CARPENTER'S QUALITY MANAGEMENT SYSTEM WAS REGISTERED AS OF NOVEMBER 24, 2007 TO THE REQUIREMENTS OF ISO 9001:2000 APPROVAL CERTIFICATE 07-0869 BY PERFORMANCE REVIEW INSTITUTE. CERTIFICATE OF TEST IS PREPARED IN ACCORDANCE WITH PARAGRAPH 3.1 OF EN 10204 (DIN 50049). WE HEREBY CERTIFY THAT THE ABOVE TEST DATA ARE IN ACCORDANCE WITH THE PURCHASE ORDER AND SPECIFICATION REQUIREMENTS.

DAISY L TALBOT
ADMINISTRATOR - QUALITY
CARPENTER TECHNOLOGY CORPORATION

3/8/11

Figure 18. Inconel 625 material certification.

Traveler(s)	Heat #	Ingot#
50305	A	91KF

CERTIFICATE OF TEST

Page 1 of 5

Prol 1 Rev 1

ATI Allvac
4374 Lancaster Highway
Richburg, SC 29729
Phone (803) 789-3595

Customer Name	Purchase Order	Size	Alloy
L. MILLER & SON, INC.	46658-4 SH610	.375" RD.	NICKELVAC C-276

LMS METAL SALES
606 TRIANA BLVD.
HUNTSVILLE, AL 35805

PCS Weight

Amend Date: 09/13/2012 Quality Auditor: Boyd Bradley

CONDITION SHIPPED

SURFACE: Centerless Ground

HEAT TREAT: 2050 F, 30 mins., WQ
(Solution Annealed)

SPECIFICATIONS

AMS 5750	C	ASME II SB-574	2010
ASTM B574	2006*1	S-1000	08/01/2011
S-400	10/10/2008		

*Corrected certification to correct tensile test results.

CHEMISTRY

CR EQ = Chromium Equiv Co + Ni

	C	S	Mn	Si	Cr	CR EQ	Mo	Co	Ti	Al	B	Zr
.	.004	<.0003	.51	.02	15.97	-	15.22	.02	<.01	.18	-	<.01

Traveler(s)	Heat #	Ingot#
50305	A	91KF

ATI Allvac 4374 Lancaster Highway Richburg, SC 29729 Phone (803) 789-3595

Page 2 of 5

	Fe	Cu	Ni	P	Cb	Ta	W	V	Cb+Ta	Ti+Al	Ni+Co	Y
.	6.32	.02	59.14	<.004	.03	<.01	3.24	.20	.04	.19	59.16	-

CHEMISTRY (TRACE)

	Bi	Pb	Sn	O	N	O/N Tested At
.	-	-	-	-	-	
.	<.00001	<.0001	<.0005	<.001	.0047	ALLVAC LOCKPORT

CHEMISTRY METHOD	ELEMENTS TESTED BY METHOD
GAS-O/N	O,N
WET-PB	PB
WET-BI	BI
WET-SN	SN
CS-CS	C,S
XRF-NI(NIBAL)	MO,W,CR,CO,FE,CU,P,NB,TA,ZR,MN,V,TI,AL,SI,NI

CHEMISTRY REMARKS

Chemistry tested at ATI ALLVAC unless otherwise noted.

CHEMISTRY ANALYTICAL METHODS
CS = Combustion/IR Detection
GAS = Inert Gas Fusion
OES = Spark Optical Emission
XRF = X-Ray Fluorescence
MET = Mass Spectroscopy(PB,BI)

Figure 19. Hastelloy C276 material certification.

Purchased from President Titanium by: L MILLER & SONS
Specs: AMS 4921L;
Description: CP GR-4 0.375" Round Bar 54"

P.O.: 23871 Date: 04/04/2013
Total Weight: 1.9

DYNAMET
A Carpenter Company

195 Museum Road
Washington, PA 15301
Phone 724.228.1000
Fax 724.228.4195

PRODUCT CERTIFICATION

WORK ORDER	SALES ORDER / RLS
048834	033121 / 1

Quality System is registered
to ISO 9001:2008 and AS9100:2004

CUSTOMER P.O.	CUSTOMER PART	QUANTITY	COILS/TAGS	LADING NO	SHIPMENT DATE
22589		326 lbs	1	00049940	07/15/2011

PART INFORMATION:041DD2APD03750
Ti CP4 Standard Grade CG Bar - 0.3750" Dia.
Specifications: AMS 4921 Rev: L; ASTM B 348 Gr4 Rev: 09; ASTM F 67 Gr4 Rev: 06; ISO 5832-2 Gr4 Rev: 99; MIL-T-9047 Gr4 Rev: G
Size: 0.3750" Dia. +/- 0.0005"
Length: 10' to 12' Random Length

Chemical Report (Wt.%)

Heat	C T	C B	Fe T	Fe B	O T	O B	N T	N B	Ot E	TOE
H16512	.048	.048	.14	.13	.38	.37	.008	.008	<.05	<.20

Ti
BAL

Hydrogen (As Shipped)

Hydrogen (%)
0.0030

As Shipped Properties

UTS #1 (psi)	YS 0.2% #1 (psi)	EL #1 (%)	RA #1 (%)
111700	94900	28	47
UTS #2 (psi)	**YS 0.2% #2 (psi)**	**EL #2 (%)**	**RA #2 (%)**
111500	94700	25	46

Hardness (HRC)
24

Metallography Results

Grain Size (ASTM)
7.5

PRESIDENT TITANIUM
APPROVED
FOR INVENTORY
DATE 07/20/11
BY JT

QTC302 (v5.2) Page 1 Date Printed [illegible]

Figure 20. TiCP material certification.

ır Order 58706-3-1 Your Order 23799 Packing List 71171-1 (3/26/2013) Img No 27410 (3/26/2013)

DYNAMET
A Carpenter Company

195 Museum Road
Washington, PA 15301

Phone 724.228.1000
Fax 724.229.4195

PRODUCT CERTIFICATION

WORK ORDER	SALES ORDER / RLS
600566	043069 / 001

TI
QA
4

Quality System is registered to ISO 9001:2008 and AS9100:2009

SOLD TO

Titanium Industries, Inc

CUSTOMER P.O.	CUSTOMER PART	QUANTITY	LADING NO	SHIPMENT DATE
CRP-23253-KS		302 lbs	00059909	02/20/2013

PART INFORMATION 121DD2FEW03750
TI 6AL 4V ELI CG Bar - 0.375" Dia.

Specifications: ASTM F 136 Rev: 12; AMS 4930 Rev: G; ASTM B 348 Gr23 Rev: 11; AMS 6932 Rev: A; ISO 5832-3 Rev: 96; BS 7252 Rev: 1997; MIL-T-9047 TI 6-4ELI Rev: G; 3.7165 Rev: 293; EN 10204 3.1 Rev: 04; MIL-T-9047 TI 6-4 Rev: G; AMS 6931 Rev: B; AMS 4928 Rev: S; SB 348 Gr 5 Rev: 2010; ASTM B 348 Gr6 Rev: 11; ASTM F 1472 Rev: 08e1; 2TA 11 Rev: 74; 2TA 12 Rev: 3
Size: 0.375" Dia. +/- 0.0005"
Length: 10' to 12' Random Length

Chemical Report (Wt.%)

Heat	Al T	Al B	C T	C B	Fe T	Fe B	N T	N B	O T	O B
H18003	6.05	6.02	.032	.028	.19	.18	.010	.009	.11	.12

V T	V B	Y T	Y B	Ti	Ot E	TOE
4.10	4.06	<.0004	<.0004	BAL	<.10	<.30

Hydrogen (As Shipped)

Hydrogen (%)
0.0023

As Shipped Properties

UTS #1 (psi)	YS 0.2% #1 (psi)	EL #1 (%)	RA #1 (%)
151300	135600	15	47
UTS #2 (psi)	**YS 0.2% #2 (psi)**	**EL #2 (%)**	**RA #2 (%)**
151500	136100	14	46

Hardness (HRC)
34

Metallography Results

Pub. ETTC 2
Microstructure: Alpha-Beta
Pub. ETTC 2 Plate: A2
Alpha Case
Material Free of Alpha Case

Material Data

Ctc307 (v6.0) Page 1 of 2 Date Printed 02/20/2013

Figure 21. Ti-6-4 material certification.

Our Order 59291-1-1 Your Order 23860

Packing List 71724-1 (4/4/2013) Img No 27667 (4/4/2013)

TI
QA
4

DYNAMET
A Carpenter Company

105 Museum Road
Washington, PA 15301
Phone 724.228.1000
Fax 724.229.4195

PRODUCT CERTIFICATION

WORK ORDER	SALES ORDER / RLS
051847	043270 / 001

SOLD TO

Titanium Industries, Inc
Corporate Materials Dept

Quality System is registered
to ISO 9001:2008 and AS9100:2009

CUSTOMER P.O.	CUSTOMER PART	QUANTITY	LADING NO	SHIPMENT DATE
CRP-23356-KS		309 lbs	00050168	03/06/2013

PART INFORMATION 121DD2ECD03760
Ti 6AL 4V ELI CG Bar - 0.375" Dia.

Specifications: ASTM F 136 Rev: 12; ASTM B 348 Gr23 Rev: 11; ISO 5832-3 Rev: 96; AMS 6932 Rev: A; AMS 4930 Rev: G; BS 7252 Rev: 1997; EN 10204 3.1 Rev: 04; MIL-T-9047 Ti 6-4ELI Rev: G
Size: 0.375" Dia. +/- 0.0005"
Length: 10' to 12' Random Length

Chemical Report (Wt.%)

Heat	Al T	Al B	C T	C B	Fe T	Fe B	K T	K B	O T	O B
H10826	6.08	6.06	.028	.029	.18	.18	.006	.007	.13	.13

V T	V B	Y T	Y B	Ti	Ot E	TOE
4.07	4.19	<.0004	<.0004	BAL	<.10	<.30

Hydrogen (As Shipped)

Hydrogen (%)
0.0022

As Shipped Properties

UTS #1 (psi)	YS 0.2% #1 (psi)	EL #1 (%)	RA #1 (%)
152300	136100	15	45
UTS #2 (psi)	**YS 0.2% #2 (psi)**	**EL #2 (%)**	**RA #2 (%)**
153800	137600	15	43

Hardness (HRC)
35

Metallography Results

Pub. ETTC 2
Microstructure: Alpha-Beta Pub. ETTC 2 Plate: A2
Alpha Case
Material Free of Alpha Case

Material Data

Qtc302 (v6.0) Page 1 of 2 Date Printed: 03/06/2013

SOLD TO: INFOPRO PO# P-20259 SO# 55599 PACKING LIST# 49075

Figure 22. Ti-6-4 ELI material certification.

Customer Name	Customer PO#	Shipper No	Heat Number
INFOPRO CORPORATION	P-20149	11	32012

Energietechnik Essen
GmbH · seit 1911

Abnahmeprüfzeugnis EN 10204/3.1
Inspection-Certificate / Certificat de réception
Nr./No. 130415 Seite/Page 1 von/of/de 1
5302016 Item 1+2

HC20028
AMS 5898 A

L. MILLER & SON, INC.
LMS METAL SALES
P. O. DRAWER 1207
HUNTSVILLE, AL 35807

Item 1: hot rolled, soft annealed
Item 2: rolled, soft annealed, drawn, ground

Stückkennzeichnung/Marking/Ident. de pièce

ETE

1	sheet 12 x 180 x 1720 mm 29 kg's	5302016 Item 1	26235	CRONIDUR 30 1.4108	
1	bar Ø 18,2 mm x random length 4 kg's	5302016 item 2	32012	CRONIDUR 30 1 4108	

Chemische Zusammensetzung in % / *Chemical Analysis % / Composition chimique %*

	C	Si	Mn	P	S	Cr	Mo	Ni	N
Check analysis 26236	0,29	0,63	0,38	0,015	0,002	15,29	0,96	0,15	0,37
32012	0,29	0,67	0,44	0,017	0,001	15,28	0,98	0,19	0,38

Prüfergebnisse / Inspection results / Résultats des essais

Heat no.:	26235 Item 1	32012 Item 2
Hardenability (HRC):	59	60
Grain size as per ASTM E 112:	..	9
Cleanliness rate as per ASTM E 45:	B1th, C1th, D1th	B1th, C1th, D1yth
Macrostructure as per ASTM A 604: Class	1A, 2-, 3-, 4-	4A, 2-, 3-, 4-
Hardness test:	..	268-271-271 HB
Frequency – severity cleanliness: As per AMS 2300	F = 0,00 / sq. inch S = 0,00 / sq. inch	F = 0,00 / sq. inch S = 0.00 / sq. inch

No decarburization and denitridation.
The product is free of carbide network.

Datum/Date Essen, 04-11-2013

ETE 7

· Elsner ·

Figure 23. Cronidur 30 material certification.

APPENDIX B—TENSILE DATA FOR NONEXPOSED SPECIMENS

Tensile data for nonexposed specimens are shown for Inconel 625 (fig. 24), Hastelloy C276 (fig. 25), TiCP (fig. 26), Ti-6-4 (fig. 27), Ti-6-4 ELI (fig. 28), and Cronidur 30 (fig. 29).

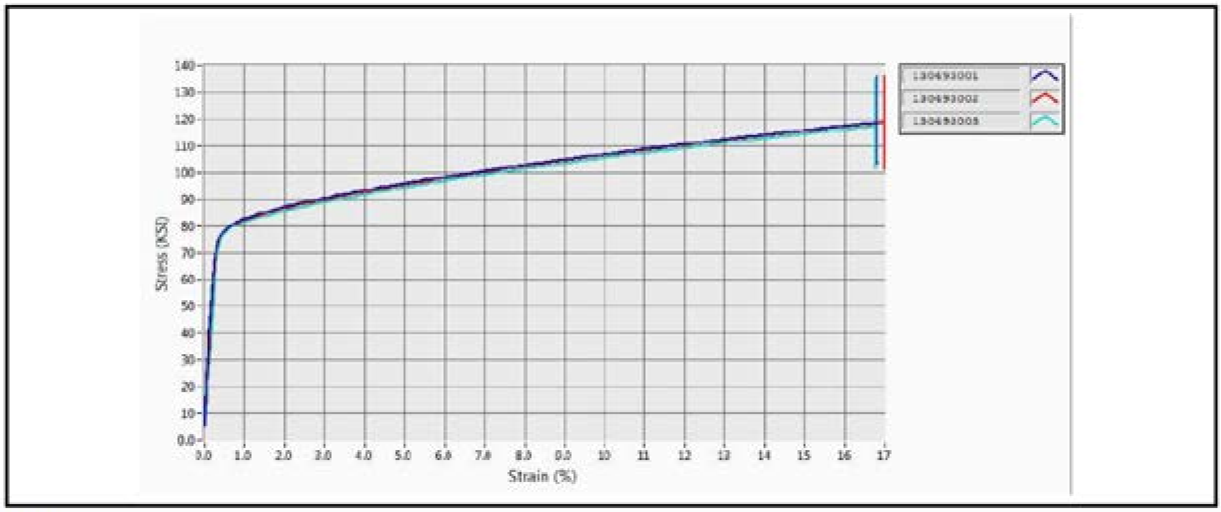
Mechanical Test Facilities

EM10

Smooth Tensile Task Results

Version 4.3

MSFC Work Order	2013-0493	Average Data Acquisition Rate (Hz)	1	Material	Inconel 625
Work Order Task	1	Control Mode	Stroke	Nominal Temperature (˚F)	72
Testing Organization	MMTF	Initial Test Rate (in/min)	0.05	Nominal Pressure (psig)	0
Customer Work Order	N/A	Final Test Rate (in/min)	0.05	Test Frame	TS-7
Test Standard	EM10 Tensile Testing Guidelines	Extensometer Gage Length (in)	0.50		



Statistics

Test Results	Maximum	Minimum	Median	Mean	Std. Deviation (sample)	Coefficient of Variation (%)
Tensile Stress (KSI)	136.25	135.51	136.25	136.00	0.42	0.31
Yield Stress (KSI)	78.23	76.68	78.23	77.71	0.89	1.15
Modulus of Elasticity (MSI)	30.47	25.87	27.88	28.07	2.30	8.20
Fracture Elongation (%)	63.80	58.55	61.67	61.34	2.64	4.31
Reduction of Area (%)	49.51	47.96	47.96	48.47	0.89	1.84

Results

* Modulus of elasticity value is for reference only. Specific modulus tests are required for true value.

EM10 Specimen ID	Other Specimen ID	Tensile Stress (KSI)	Yield Stress (KSI)	Modulus of Elasticity (MSI)*	Fracture Elongation (%)	Reduction of Area (%)
130493001	In625-1	136.25	76.68	30.47	58.55	47.96
130493002	In625-2	136.25	78.23	27.88	63.80	47.96
130493003	In625-3	135.51	78.23	25.88	61.67	49.51

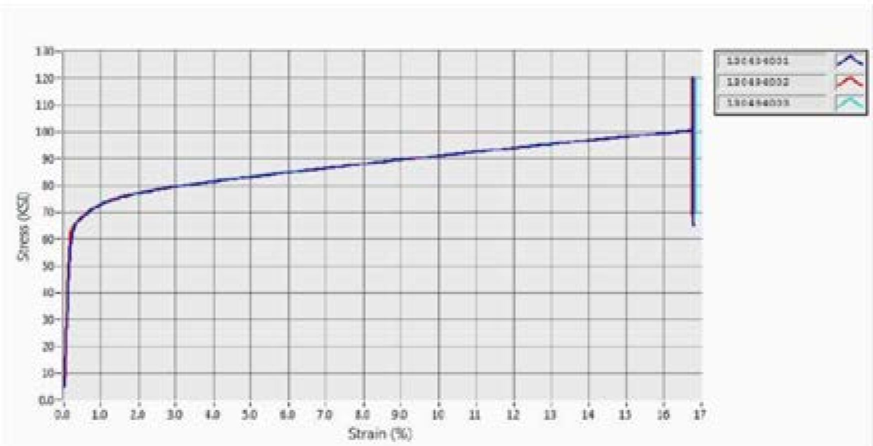
Figure 24. Inconel 625 stress-strain curves and tensile data for as-received specimens.

EM10

Smooth Tensile Task Results

Version 4.3

MSFC Work Order	2013-0494	Average Data Acquisition Rate (Hz)	1	Material	Ni Alloy: Hastelloy C276
Work Order Task	1	Control Mode	Stroke	Nominal Temperature (°F)	72
Testing Organization	MMTF	Initial Test Rate (in/min)	0.05	Nominal Pressure (psig)	0
Customer Work Order	N/A	Final Test Rate (in/min)	0.05	Test Frame	TS-7
Test Standard	EM10 Tensile Testing Guidelines	Extensometer Gage Length (in)	0.50		



Statistics

Test Results	Maximum	Minimum	Median	Mean	Std. Deviation (sample)	Coefficient of Variation (%)
Tensile Stress (KSI)	120.85	120.60	120.76	120.74	0.12	0.10
Yield Stress (KSI)	67.47	66.49	67.06	67.01	0.49	0.73
Modulus of Elasticity (MSI)	32.66	30.33	32.34	31.78	1.26	3.98
Fracture Elongation (%)	69.61	68.20	69.41	69.07	0.77	1.11
Reduction of Area (%)	61.63	59.22	60.44	60.43	1.21	2.00

Results

EM10 Specimen ID	Other Specimen ID	Tensile Stress (KSI)	Yield Stress (KSI)	Modulus of Elasticity (MSI)*	Fracture Elongation (%)	Reduction of Area (%)
130494001	C276-1	120.85	67.47	30.33	69.61	60.44
130494002	C276-2	120.60	66.49	32.66	69.41	59.22
130494003	C276-3	120.76	67.06	32.34	68.20	61.63

* Modulus of elasticity value is for reference only. Specific modulus tests are required for true value.

Figure 25. Hastelloy C276 stress-strain curves and tensile data for as-received specimens.

EM10

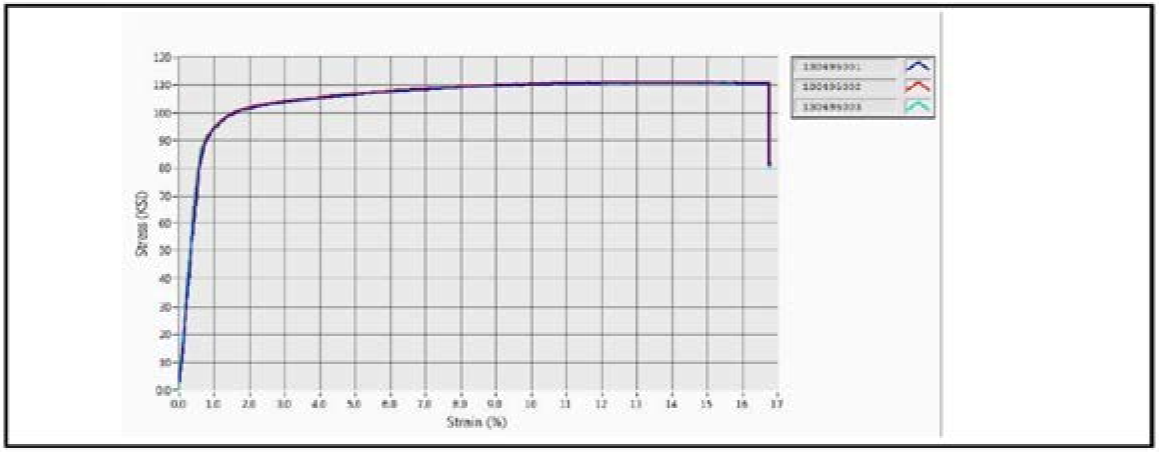
Smooth Tensile Task Results

Version 4.3

MSFC Work Order	2013-0495
Work Order Task	1
Testing Organization	MMTF
Customer Work Order	N/A
Test Standard	EM10 Tensile Testing Guidelines

Average Data Acquisition Rate (Hz)	3
Control Mode	Stroke
Initial Test Rate (in/min)	0.05
Final Test Rate (in/min)	0.05
Extensometer Gage Length (in)	0.50

Material	Ti Alloy: Commercially Pure Ti
Nominal Temperature (°F)	72
Nominal Pressure (psig)	0
Test Frame	TS-7



Statistics

Test Results	Maximum	Minimum	Median	Mean	Std. Deviation (sample)	Coefficient of Variation (%)
Tensile Stress (KSI)	111.15	110.82	110.82	110.93	0.19	0.17
Yield Stress (KSI)	91.59	91.27	91.43	91.43	0.16	0.18
Modulus of Elasticity (MSI)	15.97	14.26	15.04	15.09	0.86	5.68
Fracture Elongation (%)	39.41	33.93	38.76	37.37	2.99	8.00
Reduction of Area (%)	43.07	42.22	43.07	42.79	0.49	1.15

Results

* Modulus of elasticity value is for reference only. Specific modulus tests are required for true value.

EM10 Specimen ID	Other Specimen ID	Tensile Stress (KSI)	Yield Stress (KSI)	Modulus of Elasticity (MSI)*	Fracture Elongation (%)	Reduction of Area (%)
130495001	TiCP-1	110.82	91.43	14.26	39.41	43.07
130495002	TiCP-2	111.15	91.59	15.04	33.93	42.22
130495003	TiCP-3	110.82	91.27	15.97	38.76	43.07

Figure 26. TiCP stress-strain curves and tensile data for as-received specimens.

EM10

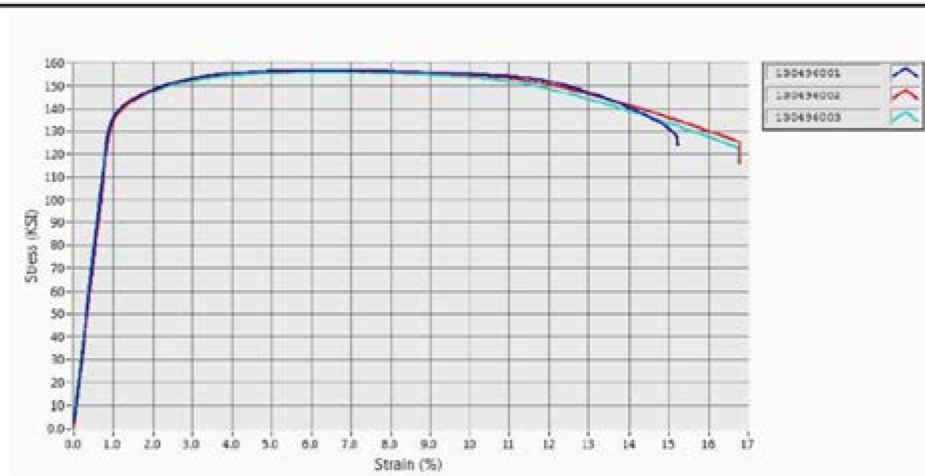
Smooth Tensile Task Results

Version 4.3

MSFC Work Order	2013-0496
Work Order Task	1
Testing Organization	MMTF
Customer Work Order	N/A
Test Standard	EM10 Tensile Testing Guidelines

Average Data Acquisition Rate (Hz)	5
Control Mode	Stroke
Initial Test Rate (in/min)	0.05
Final Test Rate (in/min)	0.05
Extensometer Gage Length (in)	0.50

Material	Ti Alloy: Ti-6Al-4V
Nominal Temperature (°F)	72
Nominal Pressure (psig)	0
Test Frame	TS-7



Statistics

Test Results	Maximum	Minimum	Median	Mean	Std. Deviation (sample)	Coefficient of Variation (%)
Tensile Stress (KSI)	156.70	155.64	156.46	156.27	0.55	0.35
Yield Stress (KSI)	138.94	137.96	138.61	138.50	0.50	0.36
Modulus of Elasticity (MSI)	15.46	14.60	15.15	15.07	0.44	2.90
Fracture Elongation (%)	18.17	16.71	16.94	17.27	0.79	4.55
Reduction of Area (%)	36.00	28.27	36.00	33.42	4.46	13.34

Results

* Modulus of elasticity value is for reference only. Specific modulus tests are required for true value.

EM10 Specimen ID	Other Specimen ID	Tensile Stress (KSI)	Yield Stress (KSI)	Modulus of Elasticity (MSI)*	Fracture Elongation (%)	Reduction of Area (%)
130496001	Ti64-1	156.70	138.94	15.46	16.94	28.27
130496002	Ti64-2	156.46	138.61	14.60	18.17	36.00
130496003	Ti64-3	155.64	137.96	15.15	16.71	36.00

Figure 27. Ti-6-4 stress-strain curves and tensile data for as-received specimens.

EM10

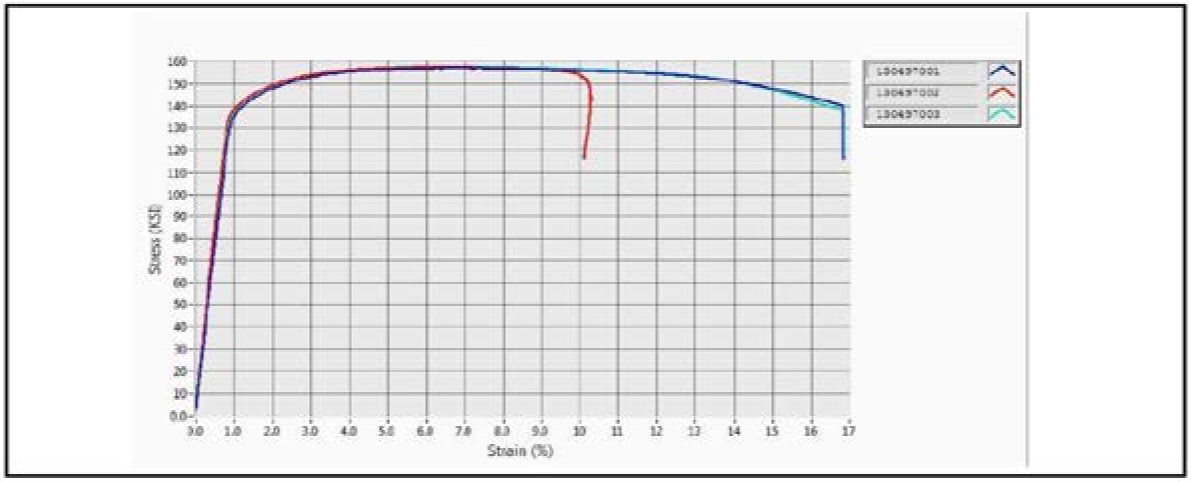
Smooth Tensile Task Results

Version 4.3

MSFC Work Order	2013-0497
Work Order Task	1
Testing Organization	MMTF
Customer Work Order	N/A
Test Standard	EM10 Tensile Testing Guidelines

Average Data Acquisition Rate (Hz)	5
Control Mode	Stroke
Initial Test Rate (in/min)	0.05
Final Test Rate (in/min)	0.05
Extensometer Gage Length (in)	0.50

Material	Ti Alloy: Ti-6Al-4V
Nominal Temperature (°F)	72
Nominal Pressure (psig)	0
Test Frame	TS-7



Statistics

Test Results	Maximum	Minimum	Median	Mean	Std. Deviation (sample)	Coefficient of Variation (%)
Tensile Stress (KSI)	157.52	156.86	157.35	157.24	0.34	0.22
Yield Stress (KSI)	139.10	138.37	138.69	138.72	0.37	0.26
Modulus of Elasticity (MSI)	16.62	14.67	16.56	15.95	1.11	6.94
Fracture Elongation (%)	20.96	18.11	19.65	19.57	1.42	7.27
Reduction of Area (%)	36.46	36.00	36.00	36.15	0.26	0.73

Results

* Modulus of elasticity value is for reference only. Specific modulus tests are required for true value.

EM10 Specimen ID	Other Specimen ID	Tensile Stress (KSI)	Yield Stress (KSI)	Modulus of Elasticity (MSI)*	Fracture Elongation (%)	Reduction of Area (%)
130497001	ELI Ti64-1	156.86	138.37	14.67	20.96	36.00
130497002	ELI Ti64-2	157.35	139.10	16.62	18.11	36.46
130497003	ELI Ti64-3	157.52	138.69	16.56	19.65	36.00

Figure 28. Ti-6-4 ELI stress-strain curves and tensile data for as-received specimens.

EM10

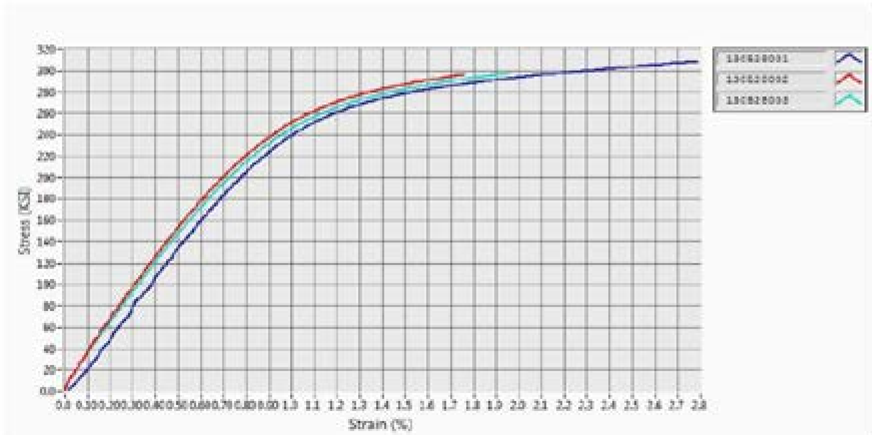
Smooth Tensile Task Results

Version 4.3

MSFC Work Order	2013-0528
Work Order Task	1
Testing Organization	MMTF
Test Standard	EM10 Tensile Testing Guidelines

Average Data Acquisition Rate (Hz)	10
Control Mode	Stroke
Initial Test Rate (in/min)	0.05
Final Test Rate (in/min)	0.05
Extensometer Gage Length (in)	0.50

Material	Fe Alloy: Cronidur 30 Steel
Nominal Temperature (°F)	72
Nominal Pressure (psig)	0
Test Frame	TS-7
Pre-Load (LBS)	1



Statistics

Test Results	Maximum	Minimum	Median	Mean	Std. Deviation (sample)	Coefficient of Variation (%)
Tensile Stress (KSI)	308.12	295.86	297.33	300.44	6.70	2.23
Yield Stress (KSI)	253.39	251.47	253.10	252.65	1.04	0.41
Modulus of Elasticity (MSI)	30.40	28.66	28.94	29.33	0.93	3.18
Fracture Elongation (%)	2.78	1.75	1.96	2.17	0.54	25.13
Reduction of Area (%)	3.20	0.81	0.82	1.61	1.38	85.62

Results

* Modulus of elasticity value is for reference only. Specific modulus tests are required for true value.

EM10 Specimen ID	Other Specimen ID	Tensile Stress (KSI)	Yield Stress (KSI)	Modulus of Elasticity (MSI)*	Fracture Elongation (%)	Reduction of Area (%)
130528001	Cronidur 30-1	308.12	253.39	28.66	2.78	3.20
130528002	Cronidur 30-2	295.86	253.10	30.40	1.75	0.82
130528003	Cronidur 30-3	297.33	251.47	28.94	1.96	0.81

Figure 29. Cronidur 30 steel stress-strain curves and tensile data for as-received specimens.

APPENDIX C—FORMULAS FOR PREPARING PRETREATED URINE

C.1 International Space Station Baseline—Current Pretreatment

Add 15.9 mL of pretreat stabilizer (54.5% DI water, 9% chromium trioxide, and 36.5% sulfuric acid) and 265 mL of DI water to 1 L of urine.

C.2 Proposed Alternate Pretreatment

Add 17.5 mL of pretreat stabilizer and 265 mL of DI water to 1 L of urine. The pretreat stabilizer will contain 2.36 mL of 85% phosphoric acid and 0.94 mL of the 30% CrO_3 oxidizer solution. The formulas for preparing pretreated urine oxidizer solution is prepared by adding 300 gm of chromium trioxide in 700 gm of ultrapure DI water.

Notes:

(1) Per these procedures, the chromium concentration in the pretreated urine is ≈800 mg/L and ≈5,000 mg/L in the brine.

(2) In the baseline pretreated urine, the sulfate concentration is ≈8,000 mg/L and ≈50,000 mg/L in the brine.

(3) For the 'alternate' pretreated urine, the phosphate concentration is ≈20,000 mg/L and the sulfate is ≈1,600 mg/L. In the alternate brine, the phosphate is ≈130,000 mg/L and the sulfate is ≈10,000 mg/L.

(Private Communication, E-mail from Donald L. Carter, MSFC-ES62, dated April 10, 2013.)

APPENDIX D—TENSILE DATA FOR EXPOSED SPECIMENS

Tensile data for exposed specimens are shown for Inconel 625 (fig. 30), Hastelloy C276 (fig. 31), TiCP (fig. 32), Ti-6-4 (fig. 33), Ti-6-4 ELI (fig. 34), and Cronidur 30 (fig. 35). The stress corrosion test conditions are also shown, as well as the average tensile data for nonexposed specimens for comparison.

EM10

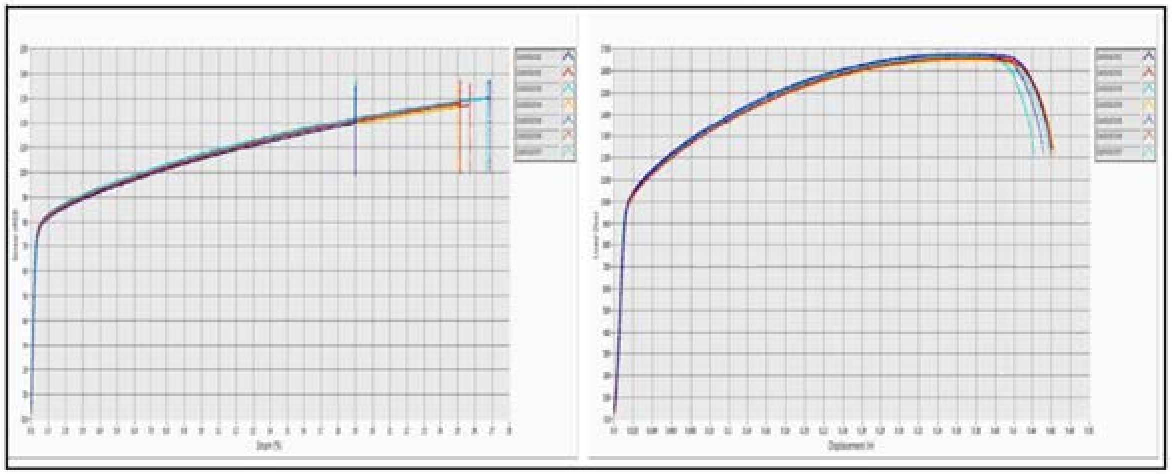
Smooth Tensile Task Results

Version 4.3

MSFC Work Order	2014-0532
Work Order Task	1
Testing Organization	EM10
Test Standard	EM10 Tensile Testing Guidlines

Average Data Acquisition Rate (Hz)	10
Control Mode	Stroke
Initial Test Rate (in/min)	0.05
Final Test Rate (in/min)	0.05
Extensometer Gage Length (in)	0.50
Specimen Gage Length (in)	0.75

Material	Inconel 625
Nominal Temperature (°F)	72
Nominal Pressure (psig)	0
Test Frame	TS-13
Drawing Number	5-48
Pre-Load (LBS)	10



Statistics

Test Results	Maximum	Minimum	Median	Mean	Std. Deviation (sample)	Coefficient of Variation (%)
Tensile Stress (KSI)	137.60	134.79	137.15	136.57	1.04	0.76
Yield Stress (KSI)	78.53	76.66	78.09	77.71	0.76	0.97
Modulus of Elasticity (MSI)	33.32	25.65	28.70	28.73	2.41	8.37
Fracture Elongation (%)	—	—	—	—	—	—
Reduction of Area (%)	64.63	53.73	61.21	60.50	3.81	6.29

Results

* Modulus of elasticity value is for reference only. Specific modulus tests are required for true value.
** Fracture elongation values exceeded the calibration limit for the extensometers used for this testing.

EM10 Specimen ID	Other Specimen ID	Tensile Stress (KSI)	Yield Stress (KSI)	Modulus of Elasticity (MSI)*	Fracture Elongation (%)**	Reduction of Area (%)
140532001	625-4	134.79	76.76	29.52	> 15.0	61.21
140532002	625-5	137.60	78.53	28.02	> 20.0	62.68
140532003	625-7	137.15	77.47	25.65	> 20.0	57.16
140532004	625-8	135.85	78.15	26.99	> 20.0	53.73
140532005	625-9	137.26	78.31	28.70	> 20.0	63.23
140532006	625-11	136.00	76.66	28.89	> 20.0	60.88
140532007	625-12	137.37	78.09	33.32	> 15.0	64.63

SCC Test Conditions for Inconel 625

Sample	Stress Level During SCC Test, %YS	Stress Level During SCC Test, ksi	Environment During SCC Test
625-4	75	58.3	Pre-Treat
625-5	75	58.3	Pre-Treat
625-7	0	0	Pre-Treat
625-8	75	58.3	Brine
625-9	75	58.3	Brine
625-11	0	0	Brine
625-12	75	58.3	Deionized Water

Averaged Tensile Data for Non Exposed Inconel 625 Specimens

UTS, ksi	YS, ksi	E, Msi	EL, %	RA, %
136.00	77.71	28.07	61.34	48.47

Figure 30. Inconel 625 stress-strain curves and tensile data after a 365-day exposure to ECLSS pretreat and brine.

EM10

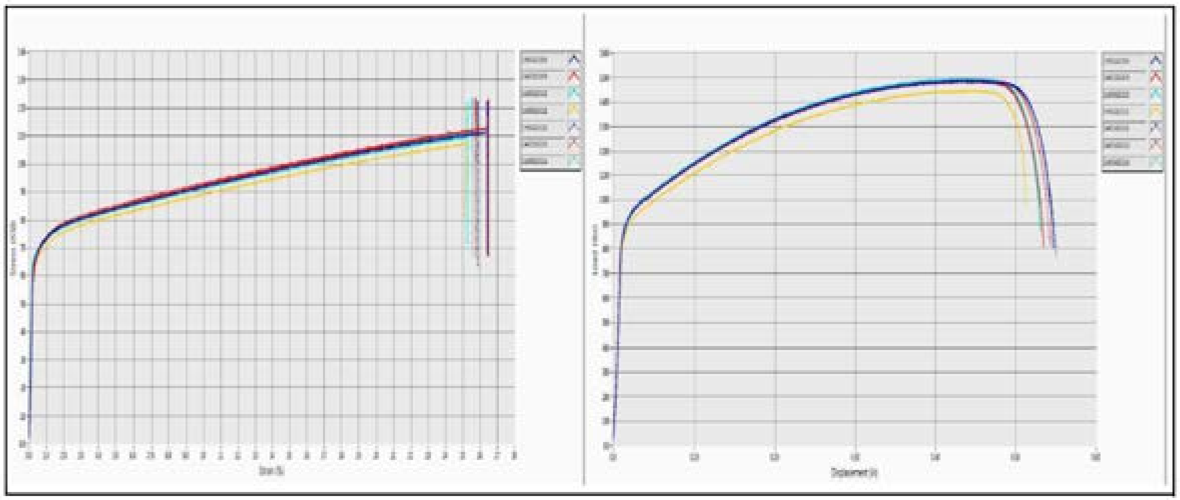
Smooth Tensile Task Results

Version 4.3

MSFC Work Order	2014-0532
Work Order Task	2
Testing Organization	EM10
Test Standard	ASTM E8

Average Data Acquisition Rate (Hz)	10
Control Mode	Stroke
Initial Test Rate (in/min)	0.05
Final Test Rate (in/min)	0.05
Extensometer Gage Length (in)	0.50
Specimen Gage Length (in)	0.75

Material	C-276
Nominal Temperature (°F)	72
Nominal Pressure (psig)	0
Test Frame	TS-13
Drawing Number	S-48
Pre-Load (LBS)	10



Statistics

Test Results	Maximum	Minimum	Median	Mean	Std. Deviation (sample)	Coefficient of Variation (%)
Tensile Stress (KSI)	123.61	120.10	122.46	122.44	1.19	0.97
Yield Stress (KSI)	68.11	65.15	67.50	67.26	1.03	1.53
Modulus of Elasticity (MSI)	32.39	25.79	28.06	28.70	2.07	7.21
Reduction of Area (%)	79.41	60.47	74.40	71.12	6.58	9.25

Results

* Modulus of elasticity value is for reference only. Specific modulus tests are required for true value.
** Fracture elongation values exceeded the calibration limit for the extensometer used for this testing.

EM10 Specimen ID	Other Specimen ID	Tensile Stress (KSI)	Yield Stress (KSI)	Modulus of Elasticity (MSI)*	Fracture Elongation (%) **	Reduction of Area (%)
140532008	276-4	122.46	67.50	27.99	> 20.0	74.40
140532009	276-5	123.08	67.17	25.79	> 20.0	75.20
140532010	276-7	122.00	66.95	30.05	> 20.0	74.60
140532011	276-8	120.10	65.15	28.06	> 20.0	65.82
140532012	276-9	122.42	68.11	28.81	> 20.0	79.41
140532013	276-11	123.61	68.08	27.81	> 20.0	67.95
140532014	276-12	123.44	67.86	32.39	> 20.0	60.47

SCC Test Conditions for Hastelloy C276

Sample	Stress Level During SCC Test, %YS	Stress Level During SCC Test, ksi	Environment During SCC Test
276-4	75	50.3	Pre-Treat
276-5	75	50.3	Pre-Treat
276-7	0	0	Pre-Treat
276-8	75	50.3	Brine
276-9	75	50.3	Brine
276-11	0	0	Brine
276-12	75	50.3	Deionized Water

Averaged Tensile Data for Non Exposed Hastelloy C276 Specimens

UTS, ksi	YS, ksi	E, Msi	EL, %	RA, %
120.74	67.01	31.78	69.07	60.43

Figure 31. Hastelloy C276 stress-strain curves and tensile data after a 365-day exposure to ECLSS pretreat and brine.

EM10

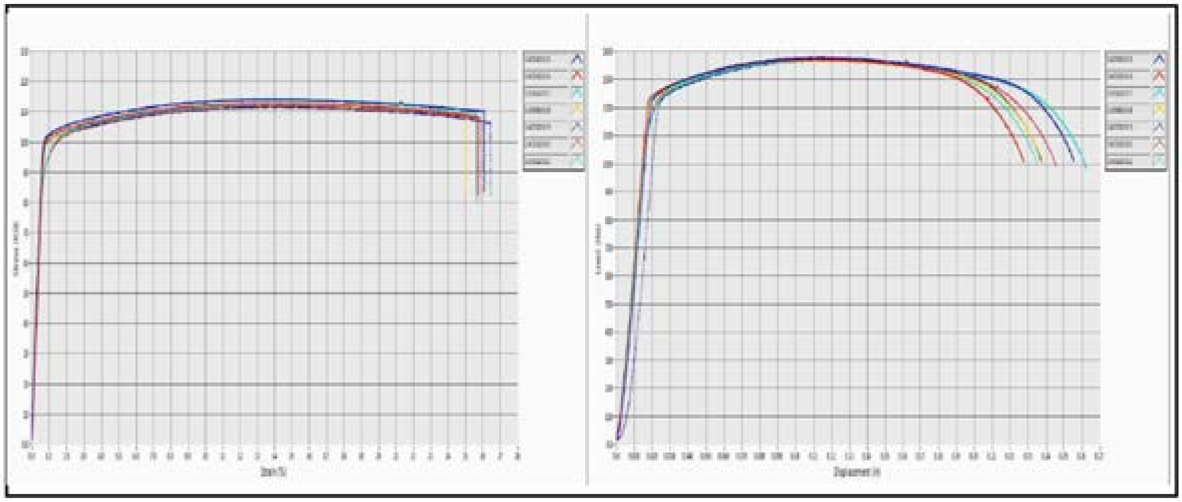
Smooth Tensile Task Results

Version 4.3

MSFC Work Order	2014-0532
Work Order Task	3
Testing Organization	EM10
Test Standard	ASTM E8

Average Data Acquisition Rate (Hz)	10
Control Mode	Stroke
Initial Test Rate (in/min)	0.05
Final Test Rate (in/min)	0.05
Extensometer Gage Length (in)	0.50
Specimen Gage Length (in)	0.75

Material	Ti-CP
Nominal Temperature (°F)	72
Nominal Pressure (psig)	0
Test Frame	TS-13
Drawing Number	5-48
Pre-Load (LBS)	10



Statistics

Test Results	Maximum	Minimum	Median	Mean	Std. Deviation (sample)	Coefficient of Variation (%)
Tensile Stress (KSI)	114.55	111.74	112.80	112.92	1.08	0.96
Yield Stress (KSI)	102.23	92.17	99.65	98.47	4.23	4.29
Modulus of Elasticity (MSI)	17.12	14.64	15.28	15.50	0.77	4.99
Reduction of Area (%)	55.83	42.55	47.90	48.09	4.74	9.86

Results

* Modulus of elasticity value is for reference only. Specific modulus tests are required for true value.
** Fracture elongation values exceeded the calibration limit for the extensometer used during this testing

EM10 Specimen ID	Other Specimen ID	Tensile Stress (KSI)	Yield Stress (KSI)	Modulus of Elasticity (MSI)*	Fracture Elongation (%) **	Reduction of Area (%)
140532015	TiCP-4	114.21	101.59	15.65	> 20.0	47.90
140532016	TiCP-5	112.81	101.53	14.64	> 20.0	51.77
140532017	TiCP-7	112.80	92.79	15.28	> 20.0	43.91
140532018	TiCP-8	112.42	99.36	15.24	> 20.0	55.83
140532019	TiCP-9	111.90	99.65	17.12	> 20.0	44.88
140532020	TiCP-11	111.74	92.17	15.24	> 20.0	42.55
140532021	TiCP-12	114.55	102.23	15.37	> 20.0	49.80

SCC Test Conditions for Titanium Commercially Pure

Sample	Stress Level During SCC Test, %YS	Stress Level During SCC Test, ksi	Environment During SCC Test
TiCP-4	75	68.6	Pre-Treat
TiCP-5	75	68.6	Pre-Treat
TiCP-7	0	0	Pre-Treat
TiCP-8	75	68.6	Brine
TiCP-9	75	68.6	Brine
TiCP-11	0	0	Brine
TiCP-12	75	68.6	Deionized Water

Averaged Tensile Data for Non Exposed Titanium Commercially Pure Specimens

UTS, ksi	YS, ksi	E, Msi	EL, %	RA, %
110.93	91.43	15.09	37.37	42.79

Figure 32. TiCP stress-strain curves and tensile data after a 365-day exposure to ECLSS pretreat and brine.

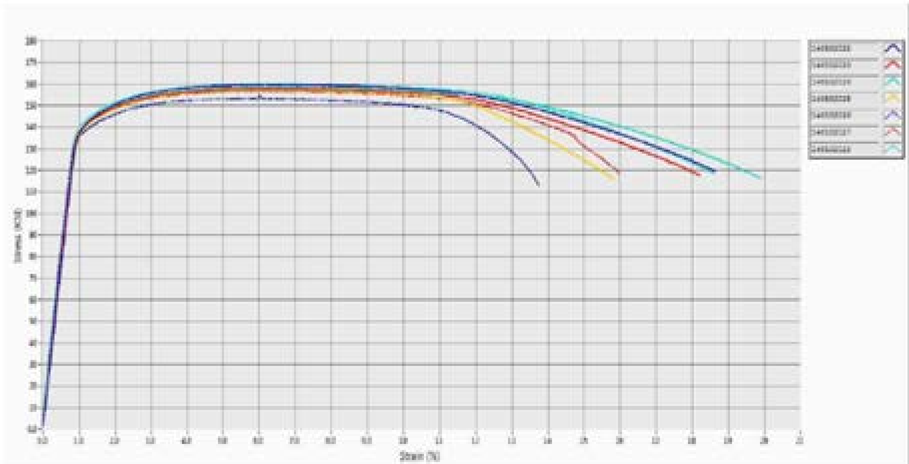
Mechanical Test Facilities

EM10

Smooth Tensile Task Results

Version 4.3

MSFC Work Order	2014-0532	Average Data Acquisition Rate (Hz)	10	Material	Ti-6Al-4V
Work Order Task	4	Control Mode	Stroke	Nominal Temperature (°F)	72
Testing Organization	EM10	Initial Test Rate (in/min)	0.05	Nominal Pressure (psig)	0
Test Standard	ASTM E8	Final Test Rate (in/min)	0.05	Test Frame	TS-13
		Extensometer Gage Length (in)	0.50	Drawing Number	5-48
		Specimen Gage Length (in)	0.75	Pre-Load (LBS)	10



Statistics

Test Results	Maximum	Minimum	Median	Mean	Std. Deviation (sample)	Coefficient of Variation (%)
Tensile Stress (KSI)	159.92	154.47	157.81	157.66	1.85	1.17
Yield Stress (KSI)	141.07	136.36	139.99	139.55	1.55	1.11
Modulus of Elasticity (MSI)	15.59	14.69	14.86	14.97	0.30	2.01
Fracture Elongation (%)	19.90	13.75	18.21	17.26	2.14	12.41
Reduction of Area (%)	45.84	32.22	39.17	38.95	4.12	10.58

Results

* Modulus of elasticity value is for reference only. Specific modulus tests are required for true value.

EM10 Specimen ID	Other Specimen ID	Tensile Stress (KSI)	Yield Stress (KSI)	Modulus of Elasticity (MSI)*	Fracture Elongation (%)	Reduction of Area (%)
140532022	Ti64-4	159.53	140.69	14.83	18.61	36.91
140532023	Ti64-5	157.81	140.09	14.86	18.21	40.76
140532024	Ti64-7	158.21	139.99	14.82	19.90	32.22
140532025	Ti64-8	157.05	139.24	14.69	15.82	37.95
140532026	Ti64-9	154.47	136.36	15.11	13.75	45.84
140532027	Ti64-11	156.65	139.42	15.59	15.97	39.81
140532028	Ti64-12	159.92	141.07	14.92	18.59	39.17

SCC Test Conditions for Titanium 6Al-4V

Sample	Stress Level During SCC Test, %YS	Stress Level During SCC Test, ksi	Environment During SCC Test
Ti64-4	75	103.9	Pre-Treat
Ti64-5	75	103.9	Pre-Treat
Ti64-7	0	0	Pre-Treat
Ti64-8	75	103.9	Brine
Ti64-9	75	103.9	Brine
Ti64-11	0	0	Brine
Ti64-12	75	103.9	Deionized Water

Averaged Tensile Data for Non Exposed Titanium 6Al-4V Specimens

UTS, ksi	YS, ksi	E, Msi	EL, %	RA, %
156.27	138.50	15.07	17.27	33.42

Figure 33. Ti-6-4 stress-strain curves and tensile data after a 365-day exposure to ECLSS pretreat and brine.

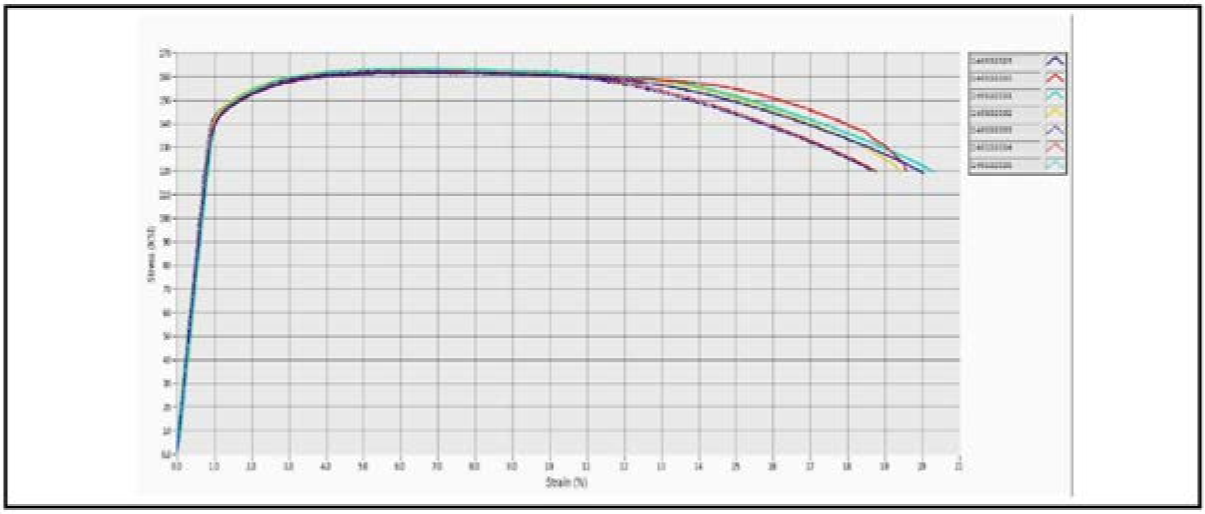
Mechanical Test Facilities

EM10

Smooth Tensile Task Results

Version 4.3

MSFC Work Order	2014-0532	Average Data Acquisition Rate (Hz)	10	Material	ELI-Ti-6-4
Work Order Task	5	Control Mode	Stroke	Nominal Temperature (°F)	72
Testing Organization	EM10	Initial Test Rate (in/min)	0.05	Nominal Pressure (psig)	0
Test Standard	ASTM E8	Final Test Rate (in/min)	0.05	Test Frame	TS-13
		Extensometer Gage Length (in)	0.50	Drawing Number	S-48
		Specimen Gage Length (in)	0.75	Pre-Load (LBS)	10



Statistics

Test Results	Maximum	Minimum	Median	Mean	Std. Deviation (sample)	Coefficient of Variation (%)
Tensile Stress (KSI)	163.59	161.71	162.61	162.57	0.76	0.47
Yield Stress (KSI)	145.56	142.51	143.73	144.02	1.20	0.83
Modulus of Elasticity (MSI)	16.18	14.83	15.01	15.20	0.46	3.01
Fracture Elongation (%)	20.32	18.63	19.56	19.55	0.66	3.38
Reduction of Area (%)	44.66	37.56	40.38	41.05	2.67	6.51

Results

* Modulus of elasticity value is for reference only. Specific modulus tests are required for true value.

EM10 Specimen ID	Other Specimen ID	Tensile Stress (KSI)	Yield Stress (KSI)	Modulus of Elasticity (MSI)*	Fracture Elongation (%)	Reduction of Area (%)
140532029	ELI-4	161.73	142.85	14.83	20.03	37.56
140532030	ELI-5	162.19	143.73	14.99	19.56	42.54
140532031	ELI-7	163.47	145.45	15.16	20.32	39.77
140532032	ELI-8	163.59	145.56	15.26	19.43	44.66
140532033	ELI-9	162.61	144.50	16.18	18.63	43.77
140532034	ELI-11	161.71	142.51	15.01	18.77	40.38
140532035	ELI-12	162.70	143.50	14.94	20.11	38.63

SCC Test Conditions for Titanium 6Al-4V Extra Low Interstitial

Sample	Stress Level During SCC Test, %YS	Stress Level During SCC Test, ksi	Environment During SCC Test
ELI-4	75	104	Pre-Treat
ELI-5	75	104	Pre-Treat
ELI-7	0	0	Pre-Treat
ELI-8	75	104	Brine
ELI-9	75	104	Brine
ELI-11	0	0	Brine
ELI-12	75	104	Deionized Water

Averaged Tensile Data for Non Exposed Titanium 6Al-4V Extra Low Interstitial Specimens

UTS, ksi	YS, ksi	E, Msi	EL, %	RA, %
157.24	138.72	15.95	19.57	36.15

Figure 34. Ti-6-4 ELI stress-strain curves and tensile data after a 365-day exposure to ECLSS pretreat and brine.

EM10

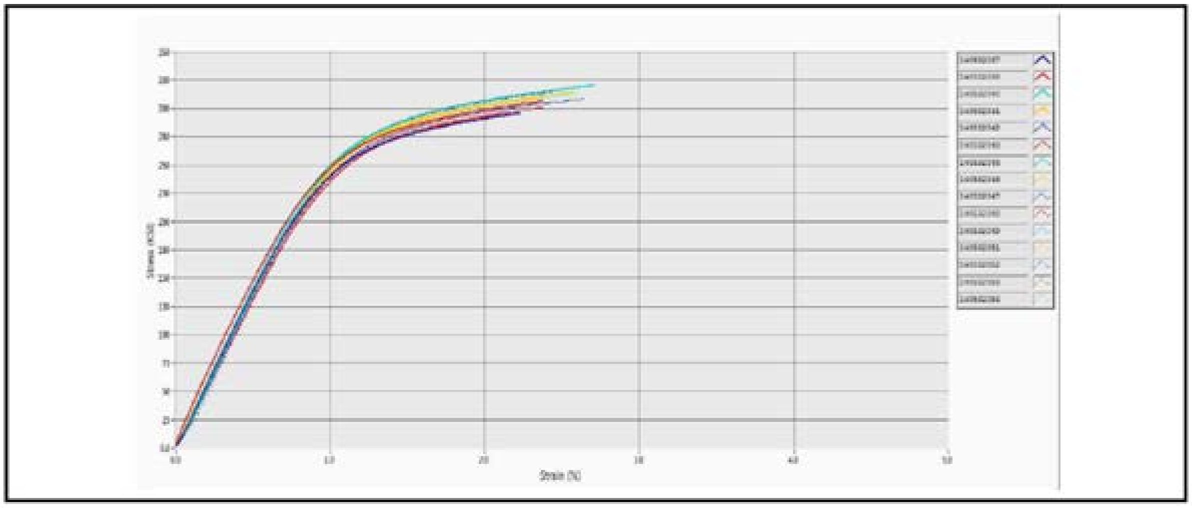
Smooth Tensile Task Results

Version 4.3

MSFC Work Order	2014-0532
Work Order Task	6
Testing Organization	EM10
Test Standard	ASTM E8

Average Data Acquisition Rate (Hz)	10
Control Mode	Stroke
Initial Test Rate (in/min)	0.05
Final Test Rate (in/min)	0.05
Extensometer Gage Length (in)	0.50

Material	Cronidur 30
Nominal Temperature (°F)	72
Nominal Pressure (psig)	0
Test Frame	TS-13
Pre-Load (LBS)	10



Statistics

Test Results	Maximum	Minimum	Median	Mean	Std. Deviation (sample)	Coefficient of Variation (%)
Tensile Stress (KSI)	320.37	174.10	300.86	286.69	41.68	14.54
Yield Stress (KSI)	265.96	248.47	258.10	258.77	5.49	2.12
Modulus of Elasticity (MSI)	28.96	26.81	28.36	28.14	0.60	2.15
Fracture Elongation (%)	2.70	0.67	2.37	2.09	0.60	28.62

Results

* Modulus of elasticity value is for reference only. Specific modulus tests are required for true value.

EM10 Specimen ID	Other Specimen ID	Tensile Stress (KSI)	Yield Stress (KSI)	Modulus of Elasticity (MSI)*	Fracture Elongation (%)
140532036	C30-4	277.08	---	---	---
140532037	C30-5	295.46	248.47	28.84	2.22
140532038	C30-7	306.18	253.52	28.90	2.37
140532039	C30-8	305.67	---	---	---
140532040	C30-9	320.37	265.96	28.37	2.70
140532041	C30-10	314.06	264.56	28.02	2.57
140532042	C30-11	314.75	265.90	28.41	2.44
140532043	C30-12	295.88	254.20	26.81	2.16
140532044	C30-13	294.08	264.12	28.96	1.61
140532045	C30-14	302.67	---	---	---
140532046	C30-15	309.72	260.70	28.40	2.37
140532047	C30-17	308.66	256.61	27.97	2.64
140532048	C30-18	300.86	254.79	27.29	2.37
140532049	C30-19	179.85	---	28.47	0.67
140532050	C30-20	174.10	---	---	---
140532051	C30-21	294.95	255.60	28.44	1.90
140532052	C30-22	288.49	258.10	27.73	1.70
140532053	C30-23	251.58	---	27.69	1.08
140532054	C30-33	312.78	261.48	27.87	2.61

Figure 35. Cronidur 30 steel stress-strain curves and tensile data after a 341-day exposure to ECLSS pretreat and brine.

Table 7 shows the SCC test conditions for Cronidur 30 steel specimens for figure 35.

Table 7. Test conditions for exposed Cronidur 30 steel specimens.

Sample	Stress Level During SCC Test (%YS)	Stress Level During SCC Test (ksi)	Environment During SCC Test
C30-4	20	50	Pretreat
C30-5	20	50	Pretreat
C30-7	10	25	Pretreat
C30-8	10	25	Pretreat
C30-9	10	25	Pretreat
C30-10	6	15	Pretreat
C30-11	6	15	Pretreat
C30-12	6	15	Pretreat
C30-13	–	–	Pretreat
C30-14	20	50	Brine
C30-15	20	50	Brine
C30-16	20	50	Brine
C30-17	10	25	Brine
C30-18	10	25	Brine
C30-19	10	25	Brine
C30-20	6	15	Brine
C30-21	6	15	Brine
C30-22	6	15	Brine
C30-23	–	–	Brine
C30-33	10	25	Deionized water

Average tensile data for nonexposed Cronidur 30 steel specimens are shown in table 8.

Table 8. Average tensile data for nonexposed Cronidur 30 steel specimens.

UTS (ksi)	YS (ksi)	E (Msi)	EL (%)	RA (%)
300.44	252.65	29.33	2.17	1.61

Table 9 shows the SCC test conditions for Cronidur 30 steel specimens for figure 36 (exposed to various environments).

Table 9. SSC test conditions for Cronidur 30 steel specimens.

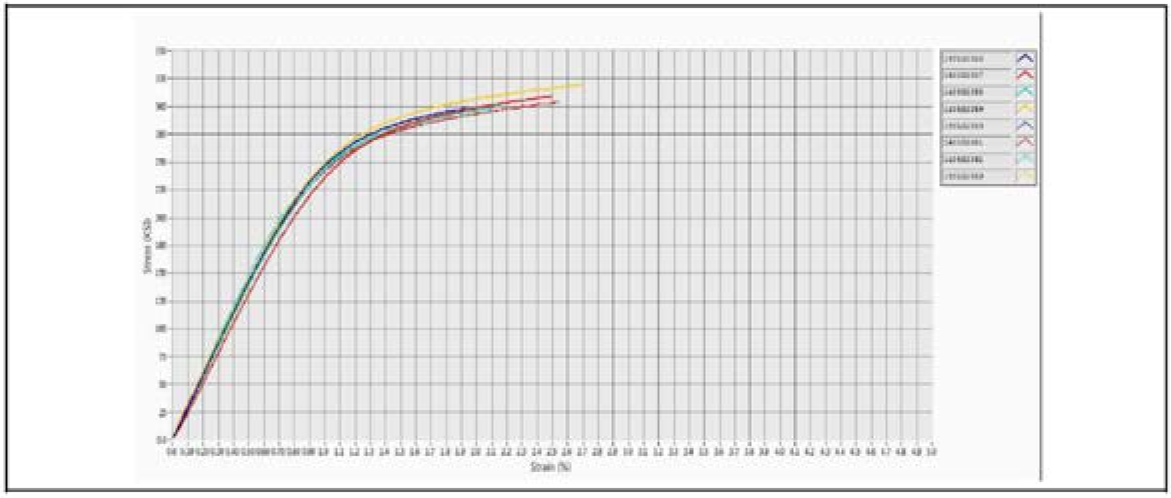
Sample	Initially Tested at 25 ksi in the Environments Shown Below Without Failing	Removed, Unloaded, Reloaded, and Subjected to the Following Environment	Stress Level for the Final Exposure (%YS)	Stress Level for the Final Exposure (ksi)
C30-24	5% salt spray at 95 ºF for 313 days	3.5% NaCl alternate immersion for 46 days	20	50
C30-25	5% salt spray at 95 ºF for 313 days	3.5% NaCl alternate immersion for 46 days	20	50
C30-26	5% salt spray at 95 ºF for 313 days	3.5% NaCl alternate immersion for 46 days	30	75
C30-27	High humidity at 95 ºF for 313 days	3.5% NaCl alternate immersion for 46 days	30	75
C30-28	High humidity at 95 ºF for 313 days	3.5% NaCl alternate immersion for 46 days	40	100
C30-29	High humidity at 95 ºF for 313 days	3.5% NaCl alternate immersion for 46 days	40	100
C30-30	3.5% NaCl alternate immersion for 313 days	3.5% NaCl alternate immersion for 46 days	50	126
C30-31	3.5% NaCl alternate immersion for 313 days	3.5% NaCl alternate immersion for 46 days	50	126
C30-32	3.5% NaCl alternate immersion for 313 days	3.5% NaCl alternate immersion for 46 days	66	166

EM10

Smooth Tensile Task Results

Version 4.3

MSFC Work Order	2014-0532	Average Data Acquisition Rate (Hz)	10	Material	Cronidur 30
Work Order Task	7	Control Mode	Stroke	Nominal Temperature (°F)	72
Testing Organization	EM10	Initial Test Rate (in/min)	0.05	Nominal Pressure (psig)	0
Test Standard	ASTM E8	Final Test Rate (in/min)	0.05	Test Frame	TS-13
		Extensometer Gage Length (in)	0.50	Pre-Load (LBS)	10



Statistics

Test Results	Maximum	Minimum	Median	Mean	Std. Deviation (sample)	Coefficient of Variation (%)
Tensile Stress (KSI)	319.74	287.46	299.72	300.95	9.73	3.23
Yield Stress (KSI)	264.27	249.29	256.44	256.18	4.44	1.73
Modulus of Elasticity (MSI)	29.86	26.85	28.30	28.35	0.96	3.38
Fracture Elongation (%)	2.70	1.65	2.13	2.15	0.40	18.52
Reduction of Area (%)	2.00	0.00	0.80	0.75	0.72	96.18

Results

* Yield Stress values for reference only. Test rate exceeded allowable stress rate per ASTM E8.
** Modulus of elasticity value is for reference only. Specific modulus tests are required for true value.

EM10 Specimen ID	Other Specimen ID	Tensile Stress (KSI)	Yield Stress (KSI)*	Modulus of Elasticity (MSI)**	Fracture Elongation (%)	Reduction of Area (%)
140532055	C30-24	304.93	---	---	---	---
140532056	C30-25	298.62	256.52	29.23	1.93	0.80
140532057	C30-26	308.49	256.36	26.85	2.49	0.80
140532058	C30-27	299.72	255.28	28.32	2.16	2.00
140532059	C30-28	319.74	264.27	27.90	2.70	0.00
140532060	C30-29	290.77	257.20	28.84	1.66	1.20
140532061	C30-30	303.56	251.97	28.29	2.55	0.00
140532062	C30-31	295.29	249.29	29.86	2.10	1.20
140532063	C30-32	287.46	258.51	27.52	1.65	0.00

Figure 36. Cronidur 30 steel stress-strain curves and tensile data after a 359-day exposure to mixed environments of 5% salt spray, high humidity, and 3.5% NaCl alternate immersion.

REFERENCES

1. ASTM G49-85 (Reapproved 2005), "Standard Practice for Preparation and Use of Direct Tension Stress-Corrosion Test Specimens," ASTM International, West Conshohocken, PA, 2005.

2. ASTM B117-11, "Standard Practice for Operating Salt Spray (Fog) Apparatus," ASTM International, West Conshohocken, PA, 2011.

3. ASTM G44-99 (Reapproved 2005), "Standard Practice for Exposure of Metals and Alloys by Alternate Immersion in Neutral 3.5 % Sodium Chloride Solution," ASTM International, West Conshohocken, PA, 2005.

4. MSFC-STD-3029, Rev A, "Guidelines for the Selection of Metallic Materials for Stress Corrosion Cracking Resistance in Sodium Chloride Environments," NASA Marshall Space Flight Center, Huntsville, AL, 2005.

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14. ABSTRACT

A stress corrosion evaluation was performed on Inconel 625, Hastelloy C276, titanium commercially pure (TiCP), Ti-6Al-4V, Ti-6Al-4V extra low interstitial, and Cronidur 30 steel as a consequence of a change in formulation of the pretreatment for processing the urine in the International Space Station Environmental Control and Life Support System Urine Processing Assembly from a sulfuric acid-based to a phosphoric acid-based solution. The first five listed were found resistant to stress corrosion in the pretreatment and brine. However, some of the Cronidur 30 specimens experienced reduction in load-carrying ability.

15. SUBJECT TERMS

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