NASA/TM—2012-215484

Effects of Long-Term Thermal Exposure on Commercially Pure Titanium Grade 2 Elevated-Temperature Tensile Properties

David L. Ellis
Glenn Research Center, Cleveland, Ohio

December 2012

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Glenn Research Center
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Acknowledgments

The author would like to acknowledge Raymond Lotenero and William Brown for their efforts in testing the samples.

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David L. Ellis
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Summary

Elevated-temperature tensile testing of commercially pure titanium (CP Ti) Grade 2 was conducted for as-received commercially produced sheet and following thermal exposure at 550 and 650 K (531 and 711 °F) for times up to 5000 h. The tensile testing revealed some statistical differences between the 11 thermal treatments, but most thermal treatments were statistically equivalent. Previous data from room temperature tensile testing was combined with the new data to allow regression and development of mathematical models relating tensile properties to temperature and thermal exposure. The results indicate that thermal exposure temperature has a very small effect, whereas the thermal exposure duration has no statistically significant effects on the tensile properties. These results indicate that CP Ti Grade 2 will be thermally stable and suitable for long-duration space missions.

Introduction

Many portions of the thermal management systems for spacecraft including ducting, recuperators, pumped loops, and heat pipes can benefit from the relatively low density and high strength-to-weight ratio of titanium (Ti). These missions can last for years or even decades with the thermal management systems operating at close to peak temperature nearly continuously. Depending on the system, the stresses from internal pressure can range from a few pascals to nearly 10 MPa (1.4 ksi). Additional external stresses may be added if the structures are utilized as load-bearing members as well. These conditions require knowledge of the elevated-temperature mechanical properties of Ti following long-term thermal exposures at moderate temperatures (400 to 650 K, or 261 to 711 °F). However, there is no comprehensive literature data available for the effects of long-term thermal exposure on the tensile properties of commercially pure titanium (CP Ti) in either Grade 1 or Grade 2. Therefore this testing was undertaken to determine the effects of thermal exposure alone on room temperature, 550 K, and 650 K (77, 531, and 711 °F) tensile properties of CP Ti Grade 2.

Pure Ti and alloys could be used in many portions of the power conversion system but mainly would be used in the heat transfer and heat rejection systems (see Fig. 1). In addition to its low density, its chemical compatibility is a key benefit of CP Ti. It is anticipated that CP Ti will not corrode or undergo minimal corrosion when in contact with ultra-high-purity He, NaK, or triple-distilled water (Ref. 1). All three fluids are potential candidates for heat transfer in various portions of the power thermal management systems under consideration by NASA’s Fission Surface Power Project, depending on the rejection temperature of the energy conversion system and the radiator operating temperature. For lunar fission surface power systems, the current maximum anticipated operating temperature is 550 K. There is a possibility that some of the components could be pushed to higher temperatures as the designs evolve or in a high-temperature excursion above 550 K by the system, so properties after exposure to 650 K were also investigated in this study.

Room temperature minimum tensile properties for CP Ti are shown in Table I. Grade 1 is preferred for power conversion systems because of its lower O content and availability of a low-Fe (0.05 wt%) version. It is felt that lower contamination of the working fluids will occur with the purer Ti. Grade 2 has some large strength advantages with minimal additional trace element levels. It was also observed from examination of available CP Ti Grade 2 sheet certifications that it is possible to purchase CP Ti that both meets the strength requirements of Grade 2 and the chemical requirements of Grade 1. This may offer the best option for space missions.

Table II gives some typical elevated-temperature tensile properties. As with the room temperature properties, CP Ti Grade 2 has a significant strength advantage over Grade 1. It also retains strengths at 811 K (1000 °F) that are very usable for many power conversion system applications. The extra temperature capability also adds a safety margin for the systems.

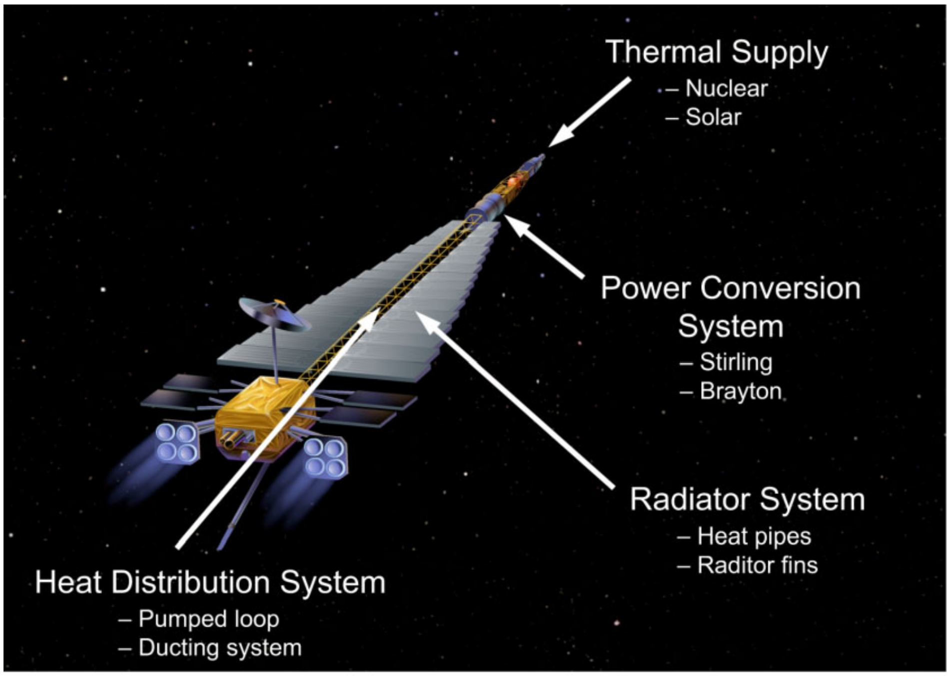

Figure 1.—Typical space power system.

TABLE I.—CP Ti ROOM TEMPERATURE MINIMUM TENSILE PROPERTIES
[From Ref. 2.]

	CP Ti Grade 1	CP Ti Grade 2
0.2% offset yield strength, MPa (ksi)	170 (25)	275 (40)
Ultimate tensile strength, MPa (ksi)	240 (35)	345 (50)
Elongation,[a] percent	24	20
Bar reduction in area, percent	30	30

[a]2-in. gauge section of sheet >0.64 mm (0.025 in.) thick.

TABLE II.—TYPICAL CP Ti ELEVATED-TEMPERATURE TENSILE PROPERTIES
[From Ref. 3.]

Property	CP Ti Grade 1			CP Ti Grade 2			
	366 K	477 K	589 K	366 K	477 K	589 K	811 K
0.2% offset yield strength, MPa	138	103.5	89.7	338	124.2	103.5	75.9
Ultimate tensile strength, MPa	262	193.2	138.0	469	207	179.4	131.1
Elongation,[a] percent	40	32	26	24	37	25	32

[a]2-in. gauge section of sheet >0.64 mm thick.

Experimental Procedure

CP Ti Grade 2 was obtained from Titanium Industries[1] as commercially rolled sheet nominally 0.89 mm (0.035 in.) thick. The sheet was provided in the annealed condition in accordance with ASTM Standard B265 (Ref. 2).

Samples approximately 76 by 152 mm (3 by 6 in.) were sheared from the larger piece. Each sample was cleaned to remove any grease. The samples were individually placed in Sentry[2] Sen/Pak heat treatment envelopes. The heat treatment envelopes are made from a high-Cr stainless steel that acts as both a protective envelope about the samples and an O getter. Alumina rods were placed between the Ti sheet samples and the stainless steel envelopes to prevent diffusion and other interactions. The envelopes were filled with nitrogen and sealed.

Two heat treatment temperatures were selected based upon prior designs to represent a typical operating temperature of 550 K (531 °F) and a maximum service temperature of 650 K (711 °F). Thermal exposures of 1000 to 5000 h in 1000-h increments were selected to assess the changes in the elevated-temperature mechanical properties with time at these temperatures.

Two furnaces were preheated to the desired temperatures and stabilized prior to loading the samples into the furnaces. Thermocouples were placed between the sample envelopes during loading. Temperatures from these thermocouples were recorded at regular intervals during the exposures using a computer-based data acquisition system.

After exposure, the samples were made into tensile test specimens by wire electrical discharge machining (EDM) specimens using the design shown in Figure 2. The design was the same as the design for the Ti-NaK compatibility study (Ref. 4) done in conjunction with this work except two holes were added for the pin-and-clevis fixtures required for elevated-temperature testing. All other dimensions were the same as the Ti-NaK and room temperature tensile test specimens.

The Ti-NaK study initiated a considerable number of room temperature tensile tests on as-received and exposed material from the same starting sheet of CP Ti used in the current study. To provide elevated-temperature data for comparison, 10 samples were secured from that program for testing at 550 and 650 K. Tensile specimens for the Ti-NaK study were machined using water jet cutting rather than wire EDM cutting since the water jet cutting was considerably faster and a large number of samples were required quickly.

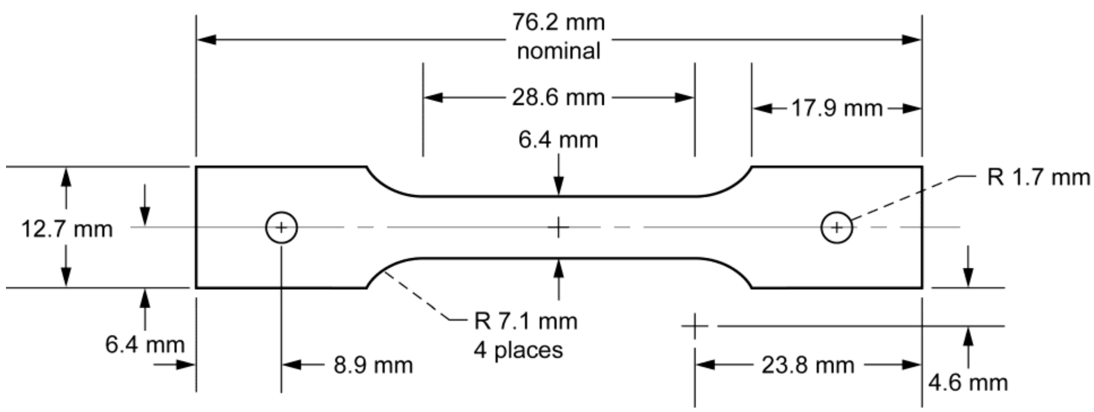

Figure 2.—Elevated-temperature tensile test specimen design.

[1] Titanium Industries, 18 Green Pond Road, Rockaway, NJ 07866.
[2] Sentry Company, 62 Main Street, Foxboro, MA 02035.

Elevated-temperature tensile testing was done using a modified Instron[3] TT series tensile test load frame. The frame had been upgraded to allow computer control and data acquisition. The upgrades also allowed strain rate control during the testing. The samples were held in the load frame using a pin-and-clevis system because the water-cooled hydraulic grips used in the room temperature tensile testing (Ref. 5) did not fit inside the furnace and also would have introduced a large thermal gradient.

Tensile testing was done at 550 and 650 K in air for this study. Room temperature testing of the same material given the same thermal exposures has previously been done and reported (Ref. 5). All tensile test conditions were identical for the prior testing except temperature.

The tensile samples were tested using a strain rate of 0.005/min. The sample test order was randomized to minimize the effects of changes in the testing with time. An MTS[4] 632.59B–04 high-temperature water-cooled extensometer with a 12.7-mm (0.5-in.) gauge length was used to measure the strain up to 19.5 percent strain, or 2.54 mm (0.098 in.) displacement. This point was well past the strain corresponding to the ultimate tensile strength and outside the uniform deformation regime of the samples. After removal of the extensometer, the strain was calculated from the crosshead movement, and this allowed strain rate control throughout the entire test.

To determine if there were statistically significant differences between the samples at each combination of thermal exposure temperature and time, three repeats were done, except for the as-received conditions where five repeats were performed. In comparison, the room temperature testing used five repeats for all combinations of thermal exposure temperature and time, as shown in Appendix A. The smaller number of tests for the elevated-temperature testing was deemed adequate based upon the room temperature results, which indicated minimal differences due to thermal exposure. The extra time and cost for elevated-temperature tensile testing also precluded using five samples. The major drawback to the lower number of tests is a lower number of degrees of freedom associated with each elevated-temperature thermal treatment and increased sensitivity to outliers. These drawbacks become most pronounced in calculating the 95% confidence intervals for the data at each exposure condition. For regression analyses and pairwise analyses, there were still a very large number of degrees of freedom, so those analyses should not be adversely affected.

Systat's[5] SigmaStat Version 3.5.1.2 was used to attempt a one-way analysis of variance (one-way ANOVA) to determine if there were statistically significant differences in the means for each condition. If normality was satisfied and the one-way ANOVA indicated that the differences in the means exceeded what could be expected from the variations inherent in each data set, a Student-Neumann-Keuls test was used to determine if there were statistically significant differences in the individual means. If normality was not satisfied, a Kruskal-Wallis one-way analysis of variance on ranks was used in place of the ANOVA to determine if the differences in means were statistically significant. When differences in the means exceeded what was expected from a random sample, either a Student-Neumann-Keuls or Dunn's analysis was used to determine which treatments were statistically equal and which were not. Based upon the room temperature results, the machining method was not considered as an independent variable in this analysis, and the data from the two as-received data sets were pooled into a single as-received data set.

Results

Results for the room temperature tensile testing were previously reported (Ref. 5), and the data set can be found in Appendix A. In this report, comparison of the tensile test data sets to discern if the means are different will only deal with the elevated-temperature tensile test data, but regression analyses will also use the room temperature data.

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[3] Instron Corporation, 825 University Ave., Norwood, MA 02062–2643.
[4] MTS Systems Corporation, 14000 Technology Drive, Eden Prarie, MN 55344.
[5] Systat Software, Inc., 1735, Technology Drive, Suite 430, San Jose, CA 95110.

Composition

The composition of the sheet as determined by NASA Glenn Research Center is presented in Table III. For comparison, the specifications for CP Ti Grades 1 and 2 are presented as well. Although the material was designated as Grade 2, it meets the chemical specifications for Grade 1.

TABLE III.—CP Ti GRADE 2 SHEET CHEMISTRY[a]

Element	NASA Glenn Research Center, wt%	Grade 1 specification,[b] wt%	Grade 2 specification,[b] wt%
Ti	Balance	Balance	Balance
C	0.0140	0.08	0.08
Fe	0.0850	0.20	0.25
N	0.0055	0.03	0.03
O	0.1300	0.18	0.20
H	0.0015	0.015	0.015
Residuals, each	0.0120	0.1	0.1
Residuals, total	0.0299	0.4	0.4

[a]Specification percentages are maximum values.
[b]From Reference 2.

Tensile Testing

All specimens exhibited high ductility and considerable necking prior to failure. Failures were consistently located in the middle half of the specimen.

Typical stress-strain curves are shown in Figure 3. Unlike the room temperature tensile tests, there is little evidence of a discontinuous yield point for the samples. A discontinuity in the stress-strain curve due to the formation of deformation twins was expected based upon the work of Paton and Backofen (Ref. 6). For pure Ti at room temperature, $(11\bar{2}2)$ twinning dominates and was the cause of the discontinuous yield observed at room temperature (Ref. 5). Paton and Backofen determined that the stress required for $(11\bar{2}2)$ twinning increases with temperature, whereas the stress for $(10\bar{1}1)$ twinning decreases with temperature until at 673 K (752 °F) $(10\bar{1}1)$ twinning accompanied by an a+c dislocation slip becomes the dominant twinning mechanism. It was expected that for this study one or both twinning mechanisms would be active depending on the test temperature, and there would be an observable discontinuous yield. Some of the stress-strain curves do show a minor discontinuity, but most do not. This indicates that the twinning mechanisms were not as prevalent or did not have as much influence on the stress-strain curves as they did at room temperature.

The results of the 550 K (531 °F) tensile testing are summarized in Figure 4, and Figure 5 summarizes the 650 K (711 °F) tensile test results. Tables IV and V contain the results for each specimen as well as the average, standard deviation, and the two-sided 95% confidence limit of each thermal exposure data set. Table IV gives results for samples given various aging heat treatments and then tested at 550 K. Table V gives results for samples given various aging heat treatments and then tested at 650 K. The bars in Figures 4 and 5 represent the average for each property at a given exposure. The error bars at the ends of each bar represent the two-sided 95% confidence interval for the average based upon a statistical analysis of the results for each data set. Based upon the data—the number of samples and their variability—there is a 95-percent probability that the results from the next test will fall within the range described by the error bars.

Many of these ranges for the strengths are small (±5 to 15 MPa, or ±0.7 to 2.2 ksi) and are consistent with normal expectations for variability in typical tensile tests. Other data sets have very large 95% confidence intervals with the largest being ±175.2 MPa (±25.4 ksi). Except where there were clear reasons to exclude a specific test result, all data were included in the comparison of the data sets to determine if thermal exposure affected tensile properties at each temperature. Because of the small

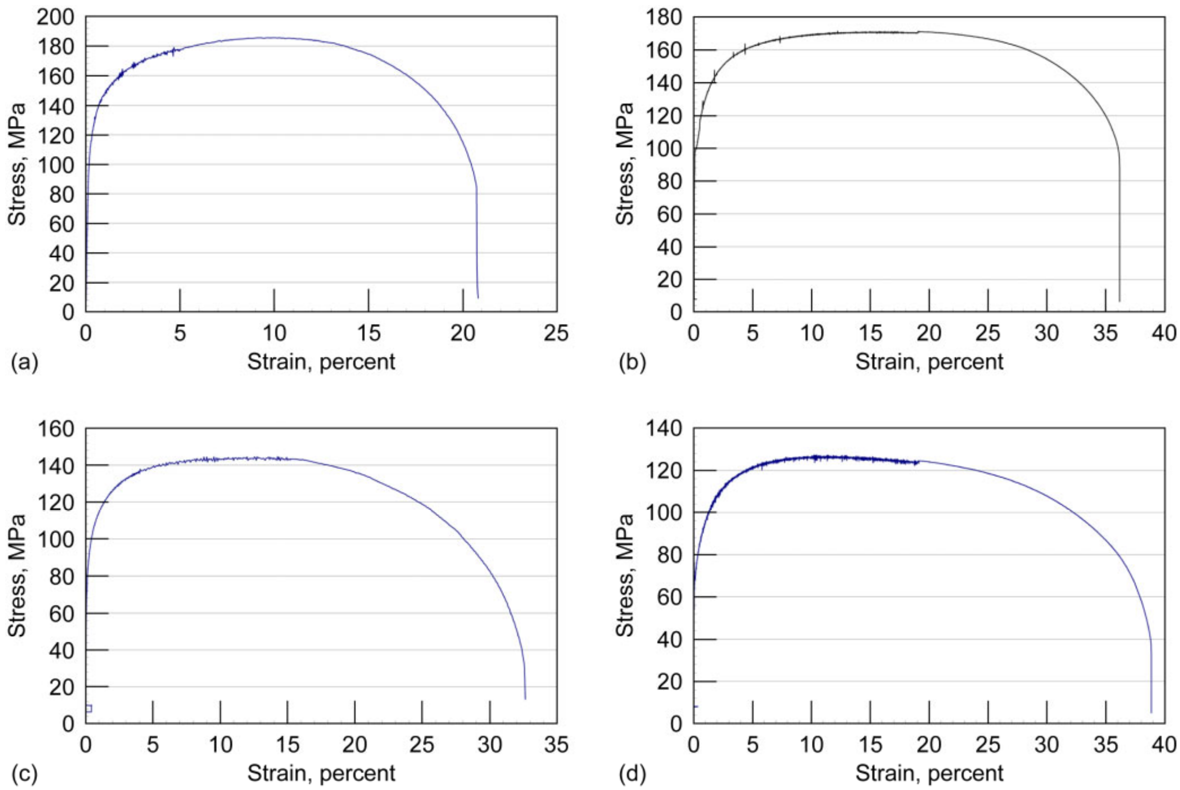

Figure 3.—CP titanium tensile tests. (a) Sample 550–1C as received, tested at 500 K. (b) Sample 550–8B exposed at 650 K for 3000 h, tested at 550 K. (c) Sample 650–2D as received, tested at 650 K. (d) Sample 650–12A exposed at 650 K for 5000 h, tested at 650 K.

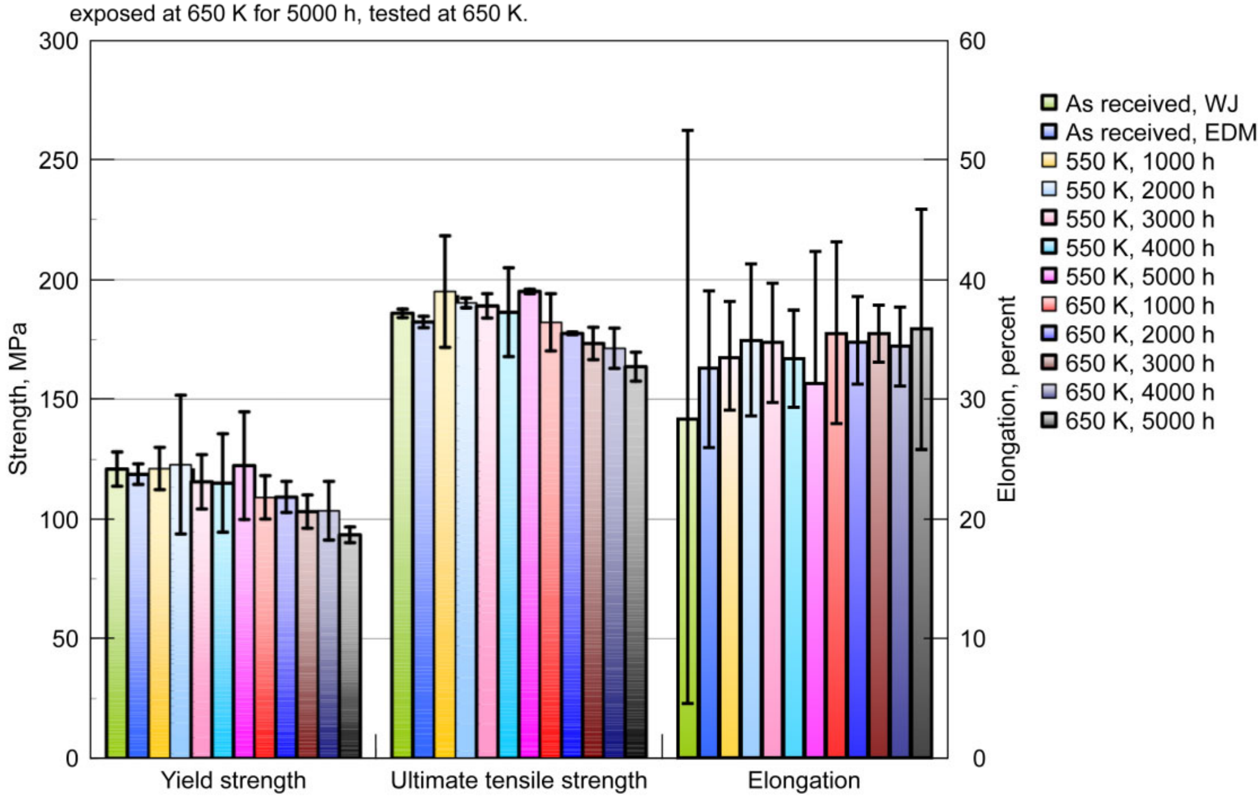

Figure 4.—500 K tensile test results for as-received (both water-jet (WJ) machined and electrical discharge machined (EDM) samples) and thermally exposed CP Ti Grade 2.

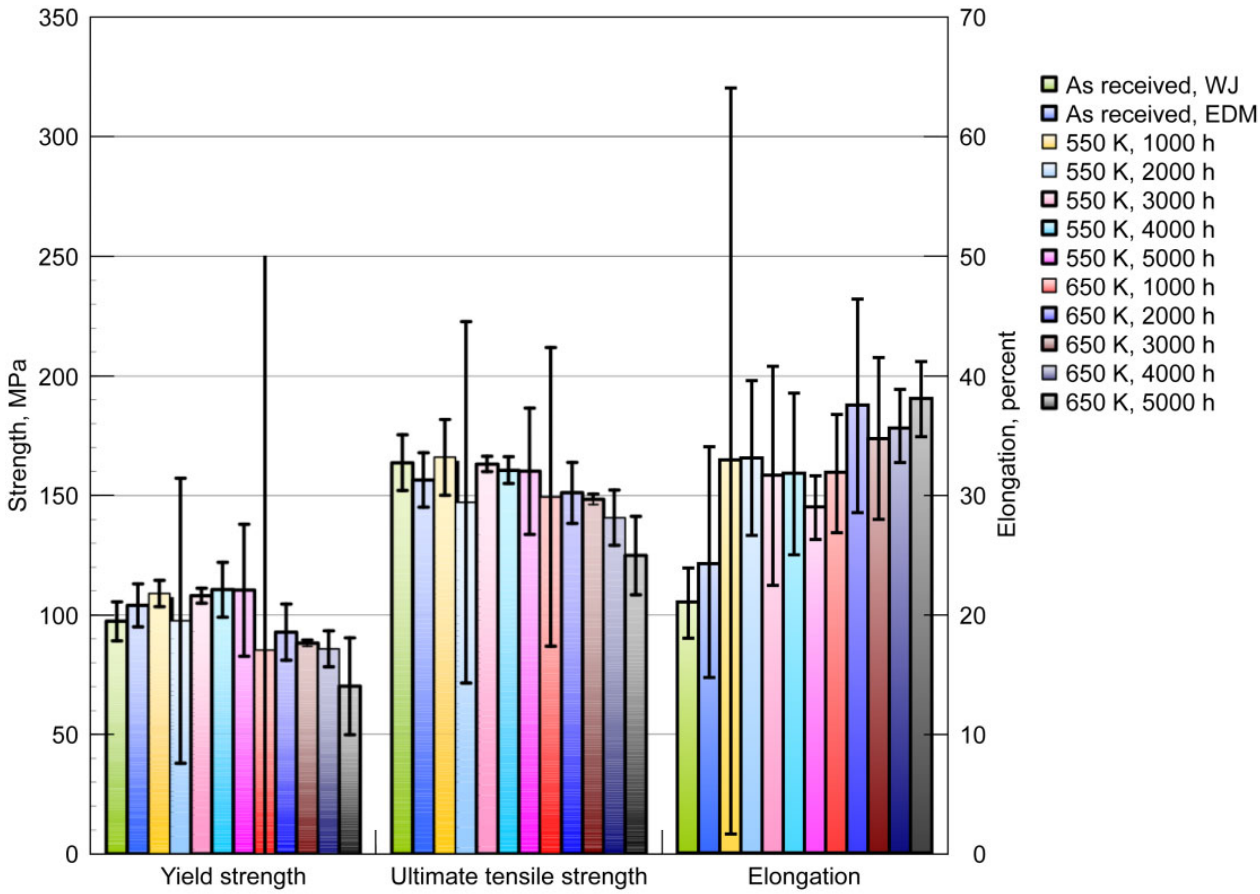

Figure 5.—500 K tensile test results for as-received (both water-jet (WJ) machined and electrical discharge machined (EDM) samples) and thermally exposed CP Ti Grade 2.

TABLE IV.—550 K TENSILE TESTING RESULTS FOR CP Ti GRADE 2

(a) As received

Sample	Yield strength, MPa	Ultimate tensile strength, MPa	Elongation, percent
Water-jet machined			
550–1A[a]			
550–1B	118.7	186.5	31.9
550–1C	122.1	185.6	[b]20.8
550–1D[a,c]			
550–1E	122.1	185.7	32.8
Average	121.0	185.9	28.5
Standard deviation	2.0	0.5	6.7
One-sided 95% interval	7.2	1.7	24.0

[a]Bad test; no data used.
[b]Suspect test.
[c]Extensometer slipped during test.

Sample	Yield strength, MPa	Ultimate tensile strength, MPa	Elongation, percent
Electrical discharge machined			
550–2A	114.9	181.3	30.9
550–2B	[b]103.9	[b]170.3	[b]32.1
550–2C	120.5	182.0	29.3
550–2D	118.7	184.5	31.5
550–2E	120.9	181.4	38.7
Average	118.7	182.3	32.6
Standard deviation	2.7	1.5	4.2
One-sided 95% interval	4.3	2.3	6.6

TABLE IV.—550 K TENSILE TESTING RESULTS FOR CP Ti GRADE 2

(b) Exposed at 550 K

Sample	Yield strength, MPa	Ultimate tensile strength, MPa	Elongation, percent
1000 h			
550–3A	123.4	202.4	35.0
550–3B	121.3	191.4	32.7
550–3C	118.5	191.0	33.2
Average	121.1	194.9	33.6
Standard deviation	2.4	6.5	1.2
One-sided 95% interval	8.8	23.3	4.4
2000 h			
550–5A	115.9	190.6	33.8
550–5B[d]			
550–5C	120.4	189.8	36.3
550–5D	131.6	190.6	33.4
Average	122.6	190.2	35.0
Standard deviation	8.1	0.6	1.8
One-sided 95% interval	29.0	2.0	6.4
3000 h			
550–7A	119.2	190.6	35.3
550–7B	114.3	188.6	33.2
550–7C	113.2	187.8	35.9
Average	115.6	189.0	34.8
Standard deviation	3.2	1.4	1.4
One-sided 95% interval	11.4	5.1	5.0

Sample	Yield strength, MPa	Ultimate tensile strength, MPa	Elongation, percent
4000 h			
550–9A	109.0	180.3	34.0
550–9B	120.5	189.6	34.2
550–9C	115.5	189.0	32.2
Average	115.0	186.3	33.5
Standard deviation	5.8	5.2	1.1
One-sided 95% interval	20.6	18.6	4.1
5000 h			
550–11A[d]			
550–11B	117.9	194.8	27.8
550–11C	119.4	195.3	33.0
550–11D	129.5	195.0	33.1
Average	122.3	195.0	31.3
Standard deviation	6.3	0.3	3.1
One-sided 95% interval	22.5	1.0	11.0

[d]Bad test; no data used.

TABLE IV.—550 K TENSILE TESTING RESULTS FOR CP Ti GRADE 2

(c) Exposed at 650 K

Sample	Yield strength, MPa	Ultimate tensile strength, MPa	Elongation, percent
1000 h			
550–4A	110.4	181.9	35.1
550–4B	110.6	185.7	33.8
550–4C	106.1	179.0	37.9
Average	109.0	182.2	35.6
Standard deviation	2.5	3.3	2.1
One-sided 95% interval	9.1	11.9	7.6
2000 h			
550–6A	110.4	177.7	34.3
550–6B	110.1	177.5	36.1
550–6C	107.1	177.4	34.3
Average	109.2	177.5	34.9
Standard deviation	1.8	0.2	1.0
One-sided 95% interval	6.5	0.6	3.7
3000 h			
550–8A	103.1	173.8	34.9
550–8B	101.2	171.3	36.2
550–8C	105.1	175.1	35.7
Average	103.1	173.4	35.6
Standard deviation	2.0	1.9	0.6
One-sided 95% interval	7.0	6.8	2.3

Sample	Yield strength, MPa	Ultimate tensile strength, MPa	Elongation, percent
4000 h			
550–10A	99.6	172.4	33.4
550–10B	106.1	168.5	35.2
550–10C	104.7	172.9	34.6
Average	103.5	171.3	34.4
Standard deviation	3.4	2.4	0.9
One-sided 95% interval	12.3	8.5	3.3
5000 h			
550–12A	94.1	161.7	36.3
550–12B	92.3	164.6	33.0
550–12C	93.5	164.7	38.6
Average	93.3	163.7	36.0
Standard deviation	0.9	1.7	2.8
One-sided 95% interval	3.3	6.1	10.1

number of tests, data that likely would have been discarded from a larger data set were retained for the analyses because there were insufficient data to conclusively determine that the points in question were indeed outliers. This led to some suspect strength data points being used in the data analyses, as indicated in Tables IV and V. In the discussion below dealing with the confidence interval calculations, it will be shown that these data points have a strong influence upon the confidence interval calculations.

Several data points exhibited unusual behavior and resulted in some of them being discarded or being deemed suspect. The results of these tests are discussed here.

Sample 650–4B has a very atypical initial response. It was unclear whether the extensometer stuck or another technical problem occurred at the start of the test. The conclusion was that the yield point was not clearly defined and therefore the yield strength was not usable. The balance of the stress-strain curve appeared normal however, so the ultimate tensile strength (UTS) and elongation values were used in the comparisons.

Samples 650–4D and 650–5D both have very low yield and UTS values that make these results suspect. Analysis of the stress-strain curves and recalculation of the strengths did not show any incorrect inputs, unusual behaviors, or mathematical miscalculations. Both samples have typical elongations that match the other samples in each data set well. Lacking sufficient data within each data set to conclusively determine that these tests were outliers, the data points were included in the comparisons.

TABLE V.—650 K TENSILE TESTING RESULTS FOR CP Ti GRADE 2

(a) As received

Sample	Yield strength, MPa	Ultimate tensile strength, MPa	Elongation, percent
Water-jet machined			
650–1A	99.4	158.1	19.9
650–1B	96.9	174.6	22.3
650–1C	88.7	168.3	23.3
650–1D	102.5	158.7	18.7
650–1E	99.2	158.6	20.3
Average	97.4	163.7	20.9
Standard deviation	5.2	7.5	1.9
One-sided 95% interval	8.2	11.7	2.9

Sample	Yield strength, MPa	Ultimate tensile strength, MPa	Elongation, percent
Electrical discharge machined			
650–2A	108.3	160.9	18.8
650–2B	103.0	156.3	26.3
650–2C	107.7	157.0	17.7
650–2D	94.3	144.7	32.7
650–2E	106.4	163.8	26.1
Average	103.9	156.5	24.3
Standard deviation	5.8	7.3	6.2
One-sided 95% interval	9.0	11.4	9.6

(b) Exposed at 550 K

Sample	Yield strength, MPa	Ultimate tensile strength, MPa	Elongation, percent
1000 h			
650–3A	108.9	170.8	[a,b]14.7
650–3B[c]			
650–3C	107.5	164.7	34.0
650–3D	110.6	162.2	31.6
Average	109.0	165.9	32.8
Standard deviation	1.5	4.4	1.7
One-sided 95% interval	5.5	15.9	31.3
2000 h			
650–5A	106.3	156.7	34.9
650–5B[c]			
650–5C	108.1	161.7	31.4
650–5D	[a]78.4	[a]122.9	32.8
Average	97.6	147.1	33.0
Standard deviation	16.7	21.1	1.8
One-sided 95% interval	59.7	75.6	6.3
3000 h			
650–7A	109.1	164.0	33.1
650–7B	107.4	163.0	32.8
650–7C	107.8	162.2	28.6
Average	108.1	163.1	31.5
Standard deviation	0.9	0.9	2.5
One-sided 95% interval	3.1	3.2	9.1

[a]Suspect test.
[b]Outlier, apparent premature failure of sample; data not used.
[c]Bad test; no data used.

Sample	Yield strength, MPa	Ultimate tensile strength, MPa	Elongation, percent
4000 h			
650–9A	112.6	161.4	32.0
650–9B†	112.2	158.8	[a,b]16.0
650–9C	106.9	161.5	31.5
Average	110.6	160.6	31.7
Standard deviation	3.2	1.5	0.4
One-sided 95% interval	11.5	5.5	6.8
5000 h			
650–11A	116.9	166.3	28.5
650–11B	112.3	162.1	29.8
650–11C	101.9	152.0	28.5
Average	110.4	160.1	28.9
Standard deviation	7.7	7.4	0.7
One-sided 95% interval	27.6	26.5	2.6

TABLE V.—650 K TENSILE TESTING RESULTS FOR CP Ti GRADE 2

(c) Exposed at 650 K

Sample	Yield strength, MPa	Ultimate tensile strength, MPa	Elongation, percent
1000 h			
650–4A	92.1	158.5	30.1
650–4B	(a)	160.3	32.5
650–4C[b]			
650–4D	[c]78.3	[c]129.2	32.5
Average	85.2	149.3	31.7
Standard deviation	9.7	17.4	1.4
One-sided 95% interval	175.2	62.5	4.9
2000 h			
650–6A	90.1	147.7	37.4
650–6B	91.9	150.7	39.8
650–6C	96.5	154.8	34.8
Average	92.8	151.1	37.3
Standard deviation	3.3	3.5	2.5
One-sided 95% interval	11.8	12.7	8.8
3000 h			
650–8A	88.1	147.7	34.8
650–8B	88.6	148.3	36.5
650–8C	87.9	149.0	32.7
Average	88.2	148.3	34.7
Standard deviation	0.4	0.6	1.9
One-sided 95% interval	1.3	2.2	6.8
4000 h			
650–10A	84.1	137.2	36.5
650–10B	85.3	141.1	35.7
650–10C	88.2	143.6	34.8
Average	85.9	140.6	35.7
Standard deviation	2.1	3.2	0.9
One-sided 95% interval	7.6	11.5	3.1
5000 h			
650–12A	74.2	127.3	38.9
650–12B	72.6	127.6	37.1
650–12C	63.7	119.5	38.0
Average	70.2	124.8	38.0
Standard deviation	5.6	4.6	0.9
One-sided 95% interval	20.2	16.5	3.2

[a]Sample had unusual yield region in stress-strain curve; yield strength not used.
[b]Bad test; no data used.
[c]Suspect test.

Sample 650–3A appeared to fail prematurely, but following maximum stress. Sample 650–9B clearly had the extensometer slip well after the peak stress was achieved, which resulted in a sudden rapid movement of the crosshead and failure of the sample. Their elongations were not used in the comparison, but the yield strength and UTS values were deemed acceptable. Sample 550–1C did not appear to fail prematurely, but it did have an unusually low elongation. Since there was no clear reason to exclude this data point, it was included in the comparisons.

Some tests were clearly bad based upon the shape of their stress-strain curves, erratic crosshead movement during the test, and so forth. Those data were excluded from these analyses. Where material was available, a fourth test was conducted to provide three accepted tests for all conditions. The exception was the 550 K as-received tests where sufficient tests were conducted so that no repeats were deemed necessary.

The normality of the individual data sets was examined next. All of the data sets except the 550 K as-received material 0.2% offset yield and ultimate tensile strengths are normal based upon a Kolmogorov-Smirnov test (Ref. 7). The normality plot shown in Figure 6(a) indicates that the yield strength for sample 650–2B is almost certainly too low. This is consistent with the observation that compared with the other yield values the value of 103 MPa (14.9 ksi) is unusually low. The value for the UTS of the specimen is also unusually low. Removal of these data points resulted in a better normality

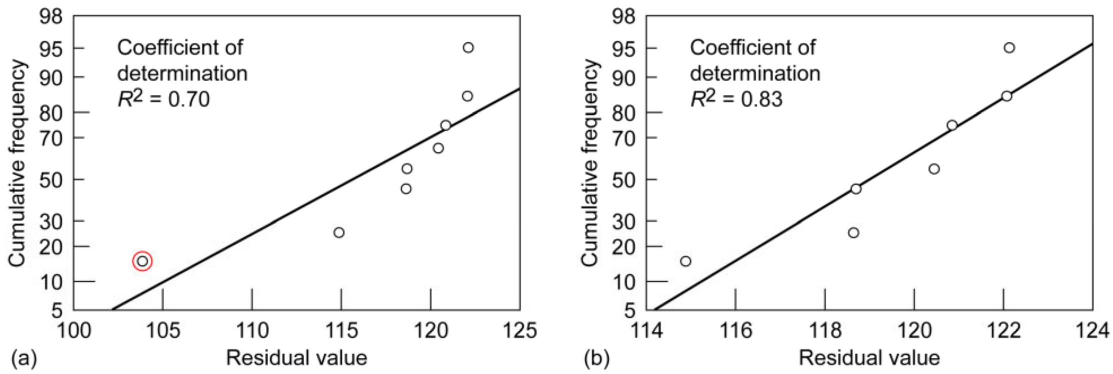

Figure 6.—Probability plot of 0.2% offset yield strength for as-received CP Ti Grade 2 at 550 K. (a) With suspect data point. (b) Without suspect point.

plot as shown in Figure 6(b), and the data sets then passed the Kolmogorov-Smirnov test. However, no physical or testing reason could be found to make such an exclusion of the specimen. The stress-strain curve also is normal and shows no reason to exclude the data point. A review of the dimensions used to calculate the stress did not indicate any data entry errors.

Despite a lack of a root cause for the low values, based upon engineering experience and the statistical analysis, the data for sample 650–2B were excluded. Confidence interval calculations and comparisons of the remaining data were then conducted.

The influence of these unusual tests on the 95% confidence intervals comes about either by increasing the variability (as measured by the standard deviation) or reducing the number of tests for a given thermal exposure as suspected outliers are excluded. The two-sided 95% confidence interval is calculated using the formula

$$CI_{95\%} = t(0.975, N-1)\frac{\sigma}{\sqrt{N}} \tag{1}$$

where N is the number of data points, $t(0.975, N-1)$ is the Student t value for $1-\alpha/2 = 0.975$ with the probability α equal to 0.05 and the degrees of freedom (ν) equal to $N-1$, and σ is the standard deviation. From this formula, the strong influence that N has directly and indirectly on the confidence interval can be seen. The values of $\sqrt{N}$ range from 1 to 3.16 whereas the value of t, which is controlled by $N-1$, ranges from 25.5 for $N = 2$ to 2.7 for $N = 10$. For the typical data set with three data points, $\sqrt{N}$ = 1.73 and $t(0.975, 2) = 6.21$. Unfortunately the largest value of t and the smallest value for $\sqrt{N}$ both occur at $N = 2$. As a result, some of the data sets shown in Figure 5 in particular have inflated confidence intervals relative to other data sets even if their standard deviations are typical. If unusual data is included for the reasons explained above, the standard deviations increase dramatically and also inflate the confidence interval relative to most data sets.

If additional testing is conducted, it is felt that the largest confidence intervals can be contracted to more typical values as N is increased, probable outliers are excluded from the data sets and the standard deviation is decreased.

The next step was to determine if there were statistically significant differences between the data collected at each elevated temperature.

A one-way ANOVA test was conducted for each tensile property (yield strength, ultimate tensile strength, and elongation) at each test temperature (550 and 650 K, or 531 and 711 °F) for a total of six analyses. Only the 550 K UTS data set passed the normality test. Table VI has the results of the one-way ANOVA for the 550 K UTS data, which indicate there are statistically significant differences among the means. For that data set, the Student-Neumann-Keuls test was used to rank the means and determine which were statistically different.

TABLE VI.—ONE-WAY ANOVA AND KRUSKAL-WALLIS ONE-WAY ANALYSIS OF VARIANCE ON RANKS RESULTS FOR 550 K TENSILE TESTS ON CP Ti GRADE 2

(a) 0.2% offset yield strength

Group	Sample number, *N*	Missing values	Median	25%	75%
As received	10	3	120.459	118.667	121.777
550 K, 1000 h	3	0	121.330	119.200	122.852
650 K, 1000 h	3	0	110.400	107.160	110.513
550 K, 2000 h	4	1	120.380	117.043	128.810
650 K, 2000 h	3	0	110.110	107.838	110.290
550 K, 3000 h	3	0	114.340	113.478	117.977
650 K, 3000 h	3	0	103.070	101.660	104.585
550 K, 4000 h	3	0	115.510	110.628	119.238
650 K, 4000 h	3	0	104.740	100.885	105.753
550 K, 5000 h	4	1	119.410	118.308	126.955
650 K, 5000 h	3	0	93.540	92.618	93.975
Normality test: failed (probability $P < 0.050$)					
$H = 29.569$ with 10 degrees of freedom ($P = 0.001$)					

(b) Ultimate tensile strength

Group	Sample number, *N*	Missing values	Mean	Standard deviation	Standard error of the mean, *SEM*
As received	10	3	183.853	2.225	0.841
550 K, 1000 h	3	0	194.937	6.502	3.754
650 K, 1000 h	3	0	182.183	3.327	1.921
550 K, 2000 h	4	1	190.323	0.471	0.272
650 K, 2000 h	3	0	177.487	0.158	0.0913
550 K, 3000 h	3	0	189.000	1.410	0.814
650 K, 3000 h	3	0	173.400	1.895	1.094
550 K, 4000 h	3	0	186.303	5.180	2.990
650 K, 4000 h	3	0	171.253	2.363	1.364
550 K, 5000 h	4	1	195.017	0.267	0.154
650 K, 5000 h	3	0	163.673	1.693	0.977
Normality test: passed ($P = 0.124$)					
Equal variance test: passed ($P = 0.547$)					

Source of variation	Degrees of freedom, ν, *DF*	Sum of squares, *SS*	Mean of squares, *MS*	*F* statistic	Probability, *P*
Between groups	10	3066.777	306.678	36.453	<0.001
Residual	26	218.740	8.413		
Total	36	3285.517			

TABLE VI.—ONE-WAY ANOVA AND KRUSKAL-WALLIS ONE-WAY ANALYSIS OF VARIANCE ON RANKS RESULTS FOR 550 K TENSILE TESTS ON CP Ti GRADE 2

(c) Elongation

Group	Sample number, *N*	Missing values	Median	25%	75%
As received	10	4	31.177	29.258	32.803
550 K, 1000 h	3	0	33.154	32.827	34.573
650 K, 1000 h	3	0	35.071	34.111	37.212
550 K, 2000 h	4	1	33.790	33.532	35.673
650 K, 2000 h	3	0	34.311	34.292	35.648
550 K, 3000 h	3	0	35.259	33.725	35.714
650 K, 3000 h	3	0	35.738	35.110	36.070
550 K, 4000 h	3	0	33.996	32.616	34.160
650 K, 4000 h	3	0	34.615	33.698	35.058
550 K, 5000 h	4	1	33.035	29.077	33.114
650 K, 5000 h	3	0	36.330	33.846	38.036
Normality test: failed ($P < 0.050$).					
$H = 14.812$ with 10 degrees of freedom ($P = 0.139$).					

For the remaining five data sets, normality was not achieved, so the one-way ANOVA was stopped, and a Kruskal-Wallis one-way analysis of variance on ranks was conducted. This test allows comparison of three or more data sets that either do not have normal distributions or do not have equal variances. The test calculates a parameter H that indicates if the null hypothesis that all means are equal is true or not. If H is small, the null hypothesis is accepted. If H is sufficiently large, the null hypothesis is rejected, and a pairwise comparison of the means is done.

The results of the Kruskal-Wallis one-way analysis of variance on ranks tests at 550 and 650 K are presented in Tables VI and VII, respectively, and they indicate that there are statistically significant differences among the medians of the tensile properties except for the elongation at 550 K. The P value (probability of being wrong in concluding there is an association between the groups) associated with each H value represents the probability of an incorrect conclusion of rejecting the null hypothesis that all medians are equal. For this analysis, $P < 0.05$ was selected as the value to conclude that there were statistically significant differences. For the remaining four properties with a statistically significant difference between the medians, a Dunn analysis was conducted to determine which medians were statistically different from the others.

One of the easier ways to present the results of the comparisons is graphically with a series of lines representing which data set means or medians are statistically equal. In Figure 7, for each property the various thermal exposures are ranked from low to high value from left to right. The numerical value of the mean or median also is given for each thermal exposure treatment. Anytime a bar is underneath the treatment, the means or medians connected by that line are statistically equal while any means to the left of the line are statistically lower than the mean and any means to the right are statistically higher than the mean. Comparisons between thermal exposures take into account all bars generated by the pairwise comparisons, so any mean or median that has any bar connecting it to a value to the left or right is statistically equal to those means. For completeness, the 550 K elongation is also provided in Figure 7(a), although the Kruskal-Wallis one-way analysis of variance on ranks had already determined that there were no statistically significant differences in the medians.

As an example, referring to Figure 7(b), at a 95% confidence level, the 550 K ultimate tensile strength mean for the as-received samples is statistically greater than the 650 K, 5000 h; 650 K, 4000 h; 650 K, 3000 h; and 650 K, 2000 h means. It is equal to the 650 K, 1000 h and 550 K, 4000 h means. It is less than the 550 K, 3000 h; 550 K, 2000 h; 550 K, 1000 h; and 550 K, 5000 h means.

TABLE VII.—ONE-WAY ANOVA AND KRUSKAL-WALLIS ONE-WAY ANALYSIS OF VARIANCE ON RANKS RESULTS FOR 650 K TENSILE TESTS ON CP Ti GRADE 2

(a) 0.2% offset yield strength

Group	Sample number, N	Missing values	Median	25%	75%
As received	10	0	100.955	96.940	106.438
550 K, 1000 h	4	1	108.910	107.838	110.155
650 K, 1000 h	4	2	85.215	78.330	92.100
550 K, 2000 h	4	1	106.290	85.350	107.625
650 K, 2000 h	3	0	91.850	90.560	95.323
550 K, 3000 h	3	0	107.790	107.498	108.735
650 K, 3000 h	3	0	88.110	87.953	88.477
550 K, 4000 h	3	0	112.230	108.233	112.530
650 K, 4000 h	3	0	85.300	84.407	87.482
550 K, 5000 h	3	0	112.320	104.483	115.740
650 K, 5000 h	3	0	72.610	65.950	73.817
Normality test: failed ($P < 0.050$)					
H = 29.562 with 10 degrees of freedom (P = 0.001)					

(b) Ultimate tensile strength

Group	Sample number, N	Missing values	Median	25%	75%
As received	10	0	158.650	156.987	163.753
550 K, 1000 h	4	1	164.660	162.837	169.295
650 K, 1000 h	4	1	158.450	136.535	159.868
550 K, 2000 h	4	1	156.680	131.368	160.468
650 K, 2000 h	3	0	150.670	148.450	153.745
550 K, 3000 h	3	0	162.990	162.420	163.763
650 K, 3000 h	3	0	148.320	147.878	148.800
550 K, 4000 h	3	0	161.380	159.430	161.485
650 K, 4000 h	3	0	141.100	138.175	142.960
550 K, 5000 h	3	0	162.120	154.500	165.285
650 K, 5000 h	3	0	127.320	121.478	127.560
Normality test: failed ($P < 0.050$)					
H = 25.933 with 10 degrees of freedom (P = 0.004)					

(c) Elongation

Group	Sample number, N	Missing values	Median	25%	75%
As received	10	0	21.279	18.761	26.115
550 K, 1000 h	4	2	32.818	31.588	34.047
650 K, 1000 h	4	1	32.462	30.680	32.480
550 K, 2000 h	4	1	32.776	31.724	34.361
650 K, 2000 h	3	0	37.355	35.473	39.174
550 K, 3000 h	3	0	32.827	29.637	33.056
650 K, 3000 h	3	0	34.845	33.241	36.065
550 K, 4000 h	3	1	31.747	31.481	32.013
650 K, 4000 h	3	0	35.653	35.012	36.301
550 K, 5000 h	3	0	28.497	28.497	29.452
650 K, 5000 h	3	0	38.033	37.313	38.647
Normality test: failed ($P < 0.050$)					
H = 31.404 with 10 degrees of freedom (P = <0.001)					

0.2% Offset yield strength (Dunn's method)

Rank	1	2	3	4	5	6	7	8	9	10	11
Treatment	650 K, 5000 h	650 K, 3000 h	650 K, 4000 h	650 K, 2000 h	650 K, 1000 h	550 K, 3000 h	550 K, 4000 h	550 K, 5000 h	550 K, 2000 h	As received	550 K, 1000 h
Median	93.5	103.1	104.7	110.1	110.4	114.3	115.5	119.4	120.4	120.5	121.3

Ultimate tensile strength (Student-Neumann-Keulls method)

Rank	1	2	3	4	5	6	7	8	9	10	11
Treatment	650 K, 5000 h	650 K, 4000 h	650 K, 3000 h	650 K, 2000 h	650 K, 1000 h	As received	550 K, 4000 h	550 K, 3000 h	550 K, 2000 h	550 K, 1000 h	550 K, 5000 h
Median	163.7	171.3	173.4	177.5	182.2	183.9	186.3	189.0	190.3	194.9	195.0

Elongation (Kruskal-Wallis one-way ANOVA on ranks)

Rank	1	2	3	4	5	6	7	8	9	10	11
Treatment	As received	550 K, 5000 h	550 K, 1000 h	550 K, 2000 h	550 K, 4000 h	650 K, 2000 h	650 K, 4000 h	650 K, 1000 h	550 K, 3000 h	650 K, 3000 h	650 K, 5000 h
Median	31.2	33.0	33.2	33.8	34.0	34.3	34.6	35.1	35.3	35.7	36.3

(a)

0.2% Offset yield strength (Dunn's method)

Rank	1	2	3	4	5	6	7	8	9	10	11
Treatment	650 K, 5000 h	650 K, 1000 h	650 K, 4000 h	650 K, 3000 h	650 K, 2000 h	As received	550 K, 2000 h	550 K, 3000 h	550 K, 1000 h	550 K, 4000 h	550 K, 5000 h
Median	72.6	85.2	85.3	88.1	91.9	101.0	106.3	107.8	108.9	112.2	112.3

Ultimate tensile strength (Dunn's method)

Rank	1	2	3	4	5	6	7	8	9	10	11
Treatment	650 K, 5000 h	650 K, 4000 h	650 K, 3000 h	650 K, 2000 h	550 K, 2000 h	650 K, 1000 h	As received	550 K, 4000 h	550 K, 5000 h	550 K, 3000 h	550 K, 1000 h
Median	127.3	141.1	148.3	150.7	156.7	158.5	158.7	161.4	162.1	163.0	164.7

Elongation (Dunn's method)

Rank	1	2	3	4	5	6	7	8	9	10	11
Treatment	As received	550 K, 5000 h	550 K, 4000 h	650 K, 1000 h	550 K, 2000 h	550 K, 1000 h	550 K, 3000 h	650 K, 3000 h	650 K, 4000 h	650 K, 2000 h	650 K, 5000 h
Median	21.3	28.5	31.7	32.5	32.8	32.8	32.8	34.8	35.7	37.4	38.0

(b)

Figure 7.—Comparison of tensile property means and median for thermally exposed CP Ti Grade 2. Values that share a line in any row have statistically equal means. Data sets are referred to by their heat treatment temperature and time. (a) 550 K tensile test data analyzed by various statistical methods. (b) Results of Dunn's method analyses for the 650 K tensile test data.

Regression Analysis

One-way ANOVA and Kruskal-Wallis one-way analysis of variance on ranks allow comparison of the properties as a function of thermal exposure. This highlights any differences between individual data sets but does not indicate any trends based upon thermal exposure time or temperatures. As done in the pairwise analyses above, these comparisons also explicitly excluded the effects of test temperature by not comparing data sets from different test temperatures.

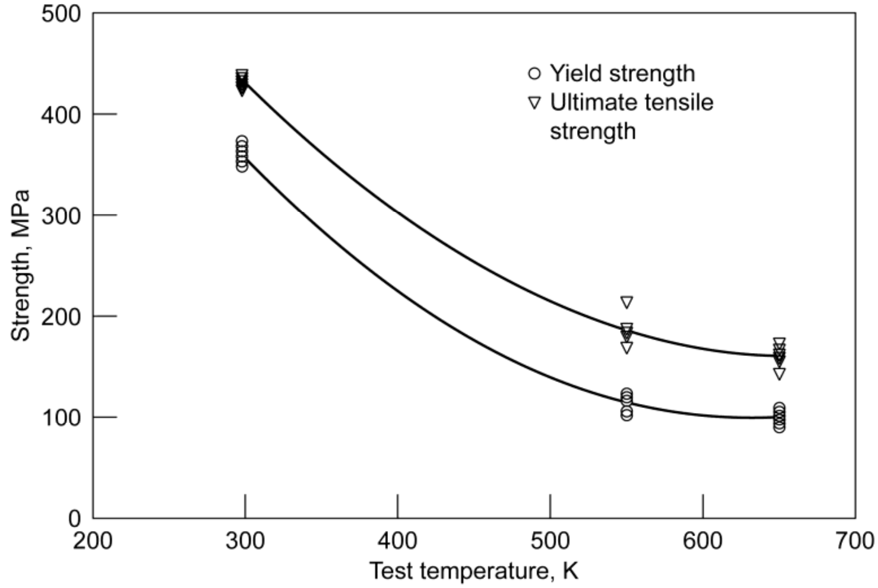

Figure 8.—Strength as function of test temperature for as-received CP Ti Grade 2.

It is possible to perform regression analyses on the data sets to predict the effects of test temperature, thermal exposure temperature, and thermal exposure time on tensile properties. First, the as-received data sets were combined with the 550 K (531 °F) and 650 K (711 °F) data sets and used to determine the proper form of the dependency of the tensile properties upon test temperature. Second, the combined tensile data were used to determine the likely form of the tensile properties upon exposure time. Finally, the difference in means for each of the 3 test temperatures and all 10 thermal exposures were plotted at each tensile test temperature as 3 bar charts to see if there appeared to be a constant offset (or no difference) caused by the difference in thermal exposure and test temperature.

The results indicated that the strengths decrease nonlinearly with test temperature as is shown by the data for the as-received data in Figure 8. Appendix B has the complete set of regression curves. This is consistent with most materials that show a nonlinear decrease in strength with temperature. A second-order equation of the form

$$\sigma = \beta_0 + \beta_1 T + \beta_2 T^2 \tag{2}$$

is the highest order polynomial that can be supported by the data that only have three test temperatures, so it was selected for the regression. The regression results for all of the data sets are presented in Table VIII. They demonstrate an excellent fit of all conditions to a second-order polynomial equation.

The results also indicate a potential linear relationship between the strength and exposure time as represented by the data in Figure 9. Based upon the regression curves, the exposure at 550 K might have a beneficial effect on strength for the 550 and 650 K tensile tests, whereas thermal exposure at 650 K is generally detrimental. The 650 K trend is more consistent with the generally observed trend of most metals having lower strength following longer thermal exposures due to grain growth, overaging of precipitates, recovery or annealing, and so forth. The regression results for the six curves and the coefficient of determination R^2 values for each regression line are presented in Table IX. The R^2 values vary and are lower than desired in several cases, but taken together, they indicate a possible dependency of strength upon exposure time. Higher order polynomial regression models were tried but provided only slight increases in the fit of the data, so a linear model was deemed appropriate.

TABLE VIII.—DEPENDENCY OF CP Ti GRADE 2 STRENGTH ON TEST TEMPERATURE

Dependent property	Exposure time, h	Exposure temperature, K	β_0, MPa	β_1, MPa/K	β_2, MPa/K²	Coefficient of determination, R^2
Yield strength	0	298	1036.4	–2.97	2.36×10^{-3}	0.9970
	1000	550	1014.2	–2.90	2.31×10^{-3}	0.9998
		650	988.1	–2.75	2.09×10^{-3}	.9993
	2000	550	947.4	–2.56	1.92×10^{-3}	0.9952
		650	1006.9	–2.87	2.26×10^{-3}	.9998
	3000	550	1014.7	–2.95	2.40×10^{-3}	0.9997
		650	1021.3	–2.96	2.34×10^{-3}	.9999
	4000	550	1067.4	–3.16	2.60×10^{-3}	0.9994
		650	1017.0	–2.92	2.28×10^{-3}	.9998
	5000	550	1006.2	–2.91	2.35×10^{-3}	0.9959
		650	995.2	–2.83	2.17×10^{-3}	.9996
Ultimate tensile strength	0	298	1063.4	–2.72	2.05×10^{-3}	0.9972
	1000	550	989.0	–2.42	1.77×10^{-3}	0.9983
		650	1014.5	–2.52	1.82×10^{-3}	.9966
	2000	550	949.0	–2.18	1.46×10^{-3}	0.9945
		650	1049.4	–2.70	2.03×10^{-3}	.9998
	3000	550	1029.9	–2.60	1.95×10^{-3}	0.9999
		650	1062.1	–2.77	2.10×10^{-3}	.9999
	4000	550	1042.2	–2.66	2.00×10^{-3}	0.9996
		650	1041.6	–2.66	1.96×10^{-3}	.9998
	5000	550	968.9	–2.30	1.63×10^{-3}	0.9972
		650	1013.9	–2.53	1.78×10^{-3}	.9997

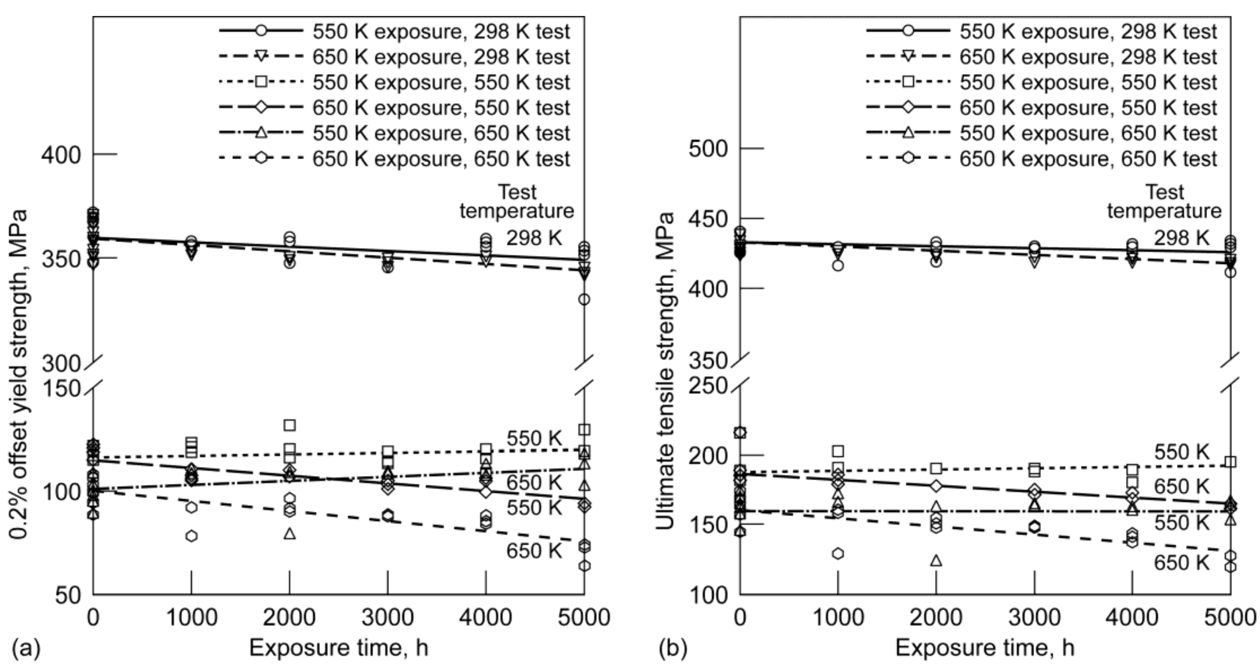

Figure 9.—Strength as function of exposure time at different temperatures for CP Ti Grade 2. (a) 0.2% offset yield strength. (b) Ultimate tensile strength.

TABLE IX.—DEPENDENCY OF CP Ti GRADE 2 STRENGTH ON EXPOSURE TIME

Dependent property	Exposure temperature, K	Test temperature, K	β_0, MPa	β_1, MPa/K	Coefficient of determination, R^2
Yield strength	550	298	359.6	-2.08×10^{-3}	0.2453
		550	116.1	7.76×10^{-4}	.0423
		650	101.0	1.95×10^{-3}	.1929
	650	298	359.3	-3.06×10^{-3}	0.5164
		550	114.8	-3.72×10^{-3}	.6118
		650	100.1	-4.88×10^{-3}	.6744
Ultimate tensile strength	550	298	433.0	-1.42×10^{-3}	0.2074
		550	187.5	9.23×10^{-4}	.0435
		650	159.8	-8.91×10^{-5}	.0003
	650	298	433.1	-2.99×10^{-3}	0.7075
		550	186.3	-4.24×10^{-3}	.5478
		650	160.2	-5.82×10^{-3}	.6391

Figure 10 shows the difference in the means of the strengths and elongations of material exposed to 550 and 650 K at each test temperature. The change in the magnitude of the difference going from testing at room temperature in Figure 10(a) to testing at 650 K in Figure 10(c) seemed to indicate a dependency of tensile properties on exposure temperature that may be nonlinear with respect to test temperature.

An attempt was made to develop a model that took into account all of these observed possible trends. The test temperature, thermal exposure time, and thermal exposure temperature were selected as the independent variables since all three may play a role. The general model entertained based upon the regression of each independent variable separately was

$$\begin{aligned} Y = \beta_0 + \beta_1 T_{\text{Test}} + \beta_2 T_{\text{Test}}^2 + \beta_3 T_{\text{Exposure}} + \beta_4 t_{\text{Exposure}} + \beta_5 T_{\text{Test}} T_{\text{Exposure}} \\ + \beta_6 T_{\text{Test}}^2 T_{\text{Exposure}} + \beta_7 T_{\text{Test}} t_{\text{Exposure}} + \beta_8 T_{\text{Test}}^2 t_{\text{Exposure}} \end{aligned} \tag{3}$$

where Y is the dependent variable (0.2% offset yield strength (MPa) or UTS (MPa)), T_{Test} is the test temperature (298, 550, or 650 K (77, 531, and 711 °F)), T_{Exposure} is the exposure temperature (298 (as received), 550, or 650 K), t_{Exposure} is the exposure time (0 (as received), 1000, 2000, 3000, 4000, or 5000 h), and β_0 through β_8 are the model coefficients that are calculated during the regression.

To account for possible two-way interactions, the product of each independent variable was included in the model. The three-way interaction between the three independent variables was also examined, but it quickly became obvious that it had a very minimal effect on the fit of the model. As a result, the three-way interaction was dropped from the model to simplify it.

The dependency of elongation on test temperature, exposure temperature, and exposure time were also examined. The as-received material data points at different test temperatures are plotted in Figure 11. The as-received elongation data were fitted using a quadratic equation with a good fit as measured by the R^2 value. Not all elongation data sets were as well explained by a quadratic equation. The complete set of regression curves in Appendix C for all exposure conditions clearly indicates that there is a dependency of elongation upon test temperature. However, the R^2 values from the regression analysis results shown in Table X indicate either that the dependency may or may not be quadratic in nature or that the dependency is weak in those data sets.

The dependency of elongation on exposure time is shown in Figure 12. The general trend is for some increase in elongation with increase in exposure time. Exposure at 650 K produced a larger increase than exposure at 550 K. The regression results are presented in Table XI.

Based upon these observations, the model in Equation (3) was deemed adequate to capture the combined effects of the independent variables upon the elongation.

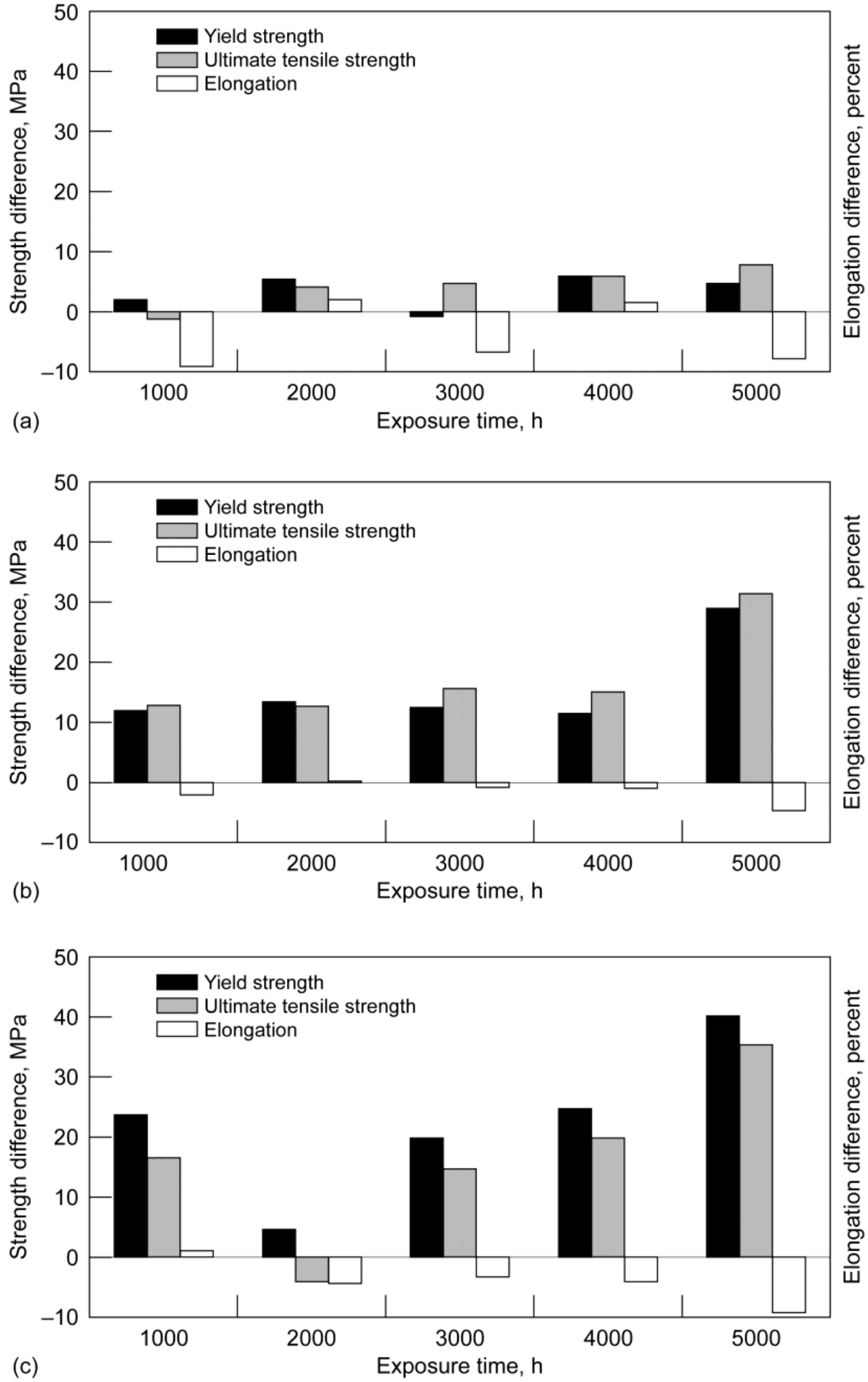

Figure 10.—Differences in mean values of tensile properties for CP Ti Grade 2 exposed to 550 and 650 K for varying times at different test temperatures. (a) Tested at room temperature. (b) Tested at 550 K. (c) Tested at 650 K.

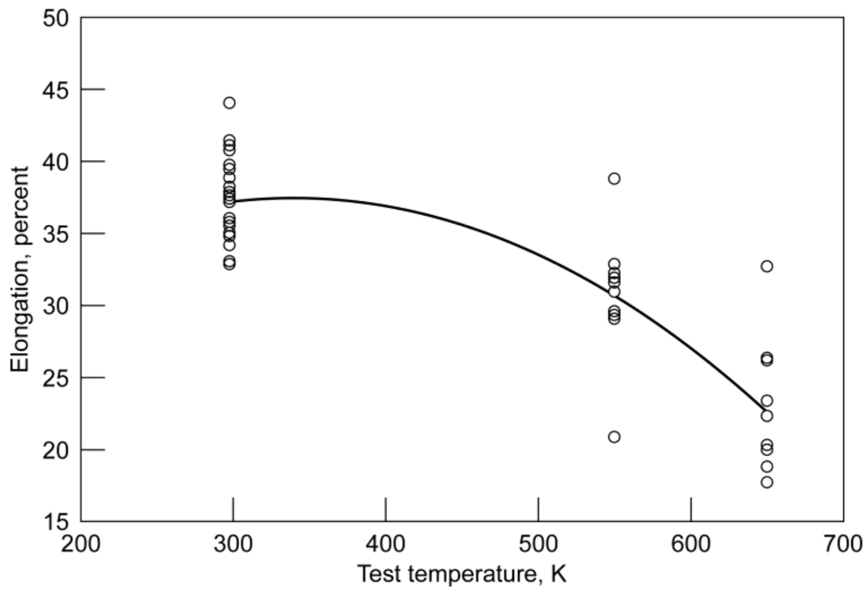

Figure 11.—Elongation as function of test temperature for as-received CP Ti Grade 2.

TABLE X.—DEPENDENCY OF CP Ti GRADE 2 ELONGATION ON TEST TEMPERATURE

Dependent property	Aging time, h	Aging temperature, K	β_0, percent	β_1, percent/K	β_2, percent/K²	Coefficient of determination, R^2
Yield strength	0	298	1036.4	–2.97	2.36×10^{-3}	0.7339
	1000	550	1014.2	–2.90	2.31×10^{-3}	0.1154
		650	988.1	–2.75	2.09×10^{-3}	.8463
	2000	550	947.4	–2.56	1.92×10^{-3}	0.7900
		650	1006.9	–2.87	2.26×10^{-3}	.3538
	3000	550	1014.7	–2.95	2.40×10^{-3}	0.4666
		650	1021.3	–2.96	2.34×10^{-3}	.8495
	4000	550	1067.4	–3.16	2.60×10^{-3}	0.9680
		650	1017.0	–2.92	2.28×10^{-3}	.9448
	5000	550	1006.2	–2.91	2.35×10^{-3}	0.8734
		650	995.2	–2.83	2.17×10^{-3}	.7929

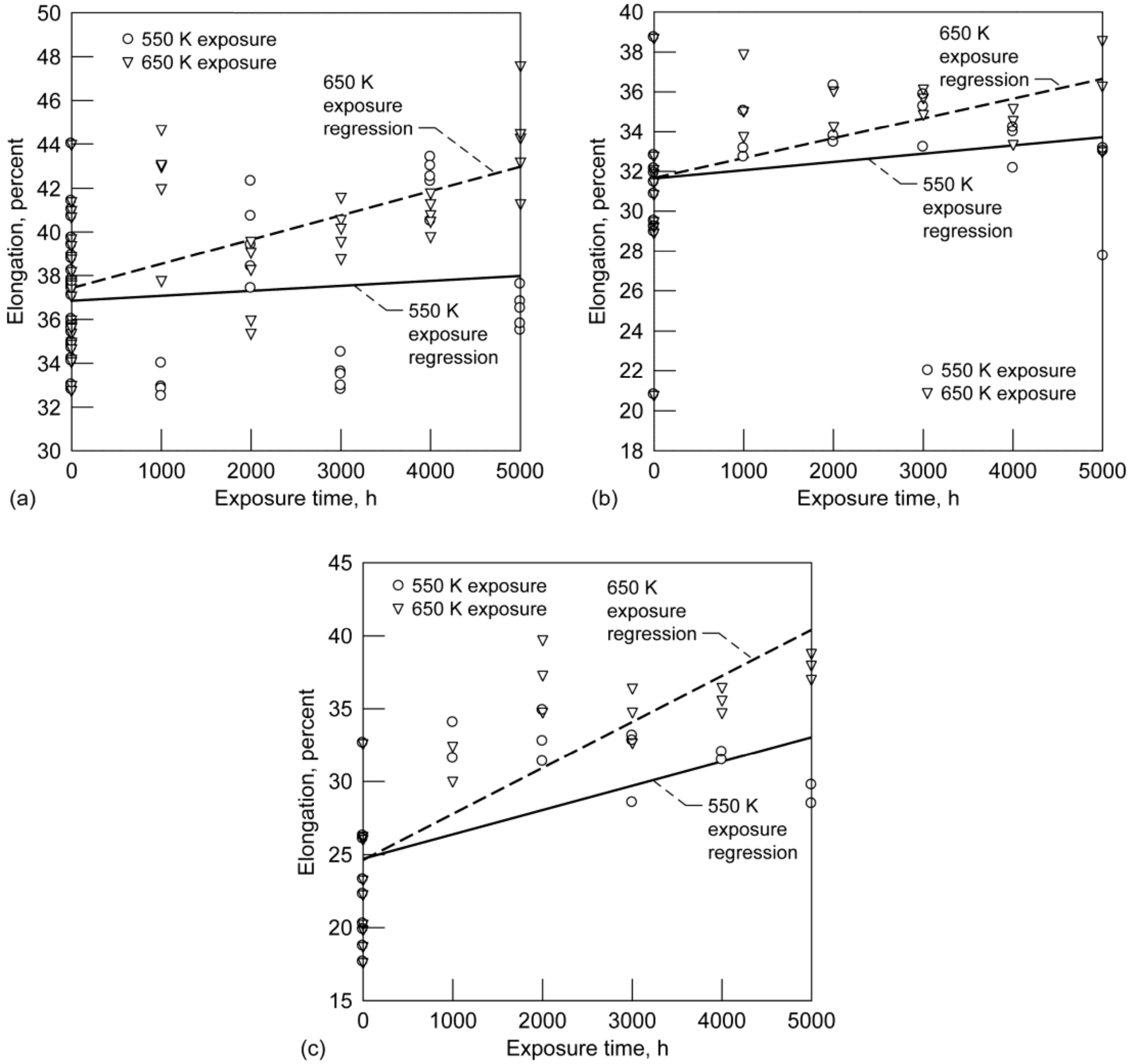

Figure 12.—Elongation of CP Ti Grade 2 at different temperatures as function of exposure time for different test temperatures. (a) Room temperature. (b) 550 K. (c) 650 K.

TABLE XI.—DEPENDENCY OF CP Ti GRADE 2 ELONGATION ON EXPOSURE TIME

Dependent property	Exposure temperature, K	Test temperature, K	β_0, percent	β_1, percent/K	Coeffficient of determination, R^2
Elongation	550	298	36.8	2.27×10^{-04}	0.0165
		550	31.6	4.15×10^{-04}	.0510
		650	24.7	1.66×10^{-03}	.3094
	650	298	37.4	1.11×10^{-03}	0.3620
		550	31.6	1.01×10^{-03}	.2489
		650	24.7	3.15×10^{-03}	.6460

Tables XII, XIII, and XIV present the results of the forward stepwise regression analyses of the yield strength, ultimate tensile strength, and elongation results, respectively. The ANOVA table from the final step is presented in the tables as well. Each independent variable has a table showing the *F* values (ratio of the estimated population variance between groups to the estimated variance within groups) for the dependent variables in the model and not in the model. The *F* values of 4.0 to enter and 3.9 to leave were used to determine which terms were to be included and which terms were to be excluded from the regressions. These *F* values gave an approximate 95% confidence in adding and removing variables. The probability values *P* for variables in the model indicate the probability that the variable was included in the model when it should not be (false positive). The probability values of variables not in the model indicate the probability that the variable should not have been in the model. The R and R^2 values give a general indication of how well the models fit the data sets.

TABLE XII.—RESULTS FOR FORWARD STEPWISE REGRESSION ANALYSES OF 0.2% OFFSET YIELD STRENGTH FOR CP Ti GRADE 2

(a) Analysis of variance[a,b]

Group	Degrees of freedom, *DF*	Sum of squares, *SS*	Mean square, *MS*	*F* distribution	Probability, *P*
Regression	3	2416176.527	805392.176	999.999	<0.001
Residual	151	11195.336	74.141		

[a] $R = 0.998$, $R^2 = 0.995$, and adjusted $R^2 = 0.995$.
[b] Standard error of estimate ($S_{Y.X}$) = 8.611.

(b) Variables in model[c]

Group	Coefficient	Standard coefficient	Standard error	*F*-to-remove	Probability, *P*
Constant	1029.053		13.037		
T_{Test}, K	–2.897	–3.585	0.0625	2146.474	<0.001
T^2_{Test}, K²	2.29×10^{-3}	2.615	6.77×10^{-5}	1143.212	<0.001
T_{Exposure}, K	–0.0296	–0.0343	4.80×10^{-3}	38.211	<0.001

[c] General model is Equation (3):

$$Y = \beta_0 + \beta_1 T_{\text{Test}} + \beta_2 T^2_{\text{Test}} + \beta_3 T_{\text{Exposure}} + \beta_4 t_{\text{Exposure}} + \beta_5 T_{\text{Test}} T_{\text{Exposure}} + \beta_6 T^2_{\text{Test}} T_{\text{Exposure}} + \beta_7 T_{\text{Test}} t_{\text{Exposure}} + \beta_8 T^2_{\text{Test}} t_{\text{Exposure}}$$

where T_{Test} is the test temperature, T_{Exposure} is the exposure temperature, t_{Exposure} is the exposure time, and β_0 through β_8 are coefficients.

(c) Variables not in model

Group	*F*-to-enter	Probability, *P*
t_{Exposure}, h	1.250	0.265
$T_{\text{Test}} * t_{\text{Exposure}}$	0.311	0.578
$T^2_{\text{Test}} * t_{\text{Exposure}}$	0.0300	0.863
$T_{\text{Test}} * T_{\text{Exposure}}$	0.104	0.748
$T^2_{\text{Test}} * T_{\text{Exposure}}$	0.134	0.714

TABLE XIII.—RESULTS FOR FORWARD STEPWISE REGRESSION ANALYSES OF CP Ti GRADE 2 ULTIMATE TENSILE STRENGTH

(a) Analysis of variance[a,b]

Group	Degrees of freedom, *DF*	Sum of squares, *SS*	Mean square, *MS*	*F* distribution	Probability, *P*
Regression	3	2657430.100	885810.033	999.999	<0.001
Residual	152	10906.605	71.754		

[a]$R = 0.998$, $R^2 = 0.996$, and adjusted $R^2 = 0.996$.
[b]Standard error of estimate ($S_{Y.X}$) = 8.471.

(b) Variables in model[c]

Group	Coefficient	Standard coefficient	Standard error	*F*-to-remove	Probability, *P*
Constant	1044.545		12.796		
T_{Test}, K	–2.580	–3.060	0.0613	1772.048	<0.001
T_{Test}^2, K²	1.90×10^{-3}	2.084	6.63×10^{-5}	821.639	<0.001
T_{Exposure}, K	–0.0325	–0.0361	4.71×10^{-3}	47.793	<0.001

[c]General model is Equation (3):

$$Y = \beta_0 + \beta_1 T_{\text{Test}} + \beta_2 T_{\text{Test}}^2 + \beta_3 T_{\text{Exposure}} + \beta_4 t_{\text{Exposure}} + \beta_5 T_{\text{Test}} T_{\text{Exposure}} + \beta_6 T_{\text{Test}}^2 T_{\text{Exposure}} + \beta_7 T_{\text{Test}} t_{\text{Exposure}} + \beta_8 T_{\text{Test}}^2 t_{\text{Exposure}}$$

where T_{Test} is the test temperature, T_{Exposure} is the exposure temperature, t_{Exposure} is the exposure time, and β_0 through β_8 are coefficients.

(c) Variables not in model

Group	*F*-to-enter	Probability, *P*
t_{Exposure}, h	1.250	0.265
$T_{\text{Test}} * t_{\text{Exposure}}$	0.311	0.578
$T_{\text{Test}}^2 * t_{\text{Exposure}}$	0.0300	0.863
$T_{\text{Test}} * T_{\text{Exposure}}$	0.104	0.748
$T_{\text{Test}}^2 * T_{\text{Exposure}}$	0.134	0.714

TABLE XIV.—RESULTS FOR FORWARD STEPWISE REGRESSION ANALYSES OF CP Ti GRADE 2 ELONGATION

(a) Analysis of variance[a,b]

Group	Degrees of freedom, *DF*	Sum of squares, *SS*	Mean square, *MS*	*F* distribution	Probability, *P*
Regression	2	2839.132	1419.566	139.460	<0.001
Residual	151	1537.037	10.179		

[a]$R = 0.805$, $R^2 = 0.649$, and adjusted $R^2 = 0.644$.
[b]Standard error of estimate ($S_{Y.X}$) = 3.190.

(b) Variables in model[c]

Group	Coefficient	Standard coefficient	Standard error	*F*-to-remove	Probability, *P*
Constant	40.720		0.483		
T_{Test}, K	-6.20×10^{-5}	–1.659	4.06×10^{-6}	233.630	<0.001
T_{Test}^2, K²	7.31×10^{-8}	1.162	6.83×10^{-9}	114.567	<0.001

[c]General model is Equation (3):

$$Y = \beta_0 + \beta_1 T_{\text{Test}} + \beta_2 T_{\text{Test}}^2 + \beta_3 T_{\text{Exposure}} + \beta_4 t_{\text{Exposure}} + \beta_5 T_{\text{Test}} T_{\text{Exposure}} + \beta_6 T_{\text{Test}}^2 T_{\text{Exposure}} + \beta_7 T_{\text{Test}} t_{\text{Exposure}} + \beta_8 T_{\text{Test}}^2 t_{\text{Exposure}}$$

where T_{Test} is the test temperature, T_{Exposure} is the exposure temperature, t_{Exposure} is the exposure time, and β_0 through β_8 are coefficients.

(c) Variables not in model

Group	*F*-to-enter	Probability, *P*
T_{Test}, K	0.0343	0.853
T_{Exposure}, K	0.0870	0.768
t_{Exposure}, h	0.297	0.587
$T_{\text{Test}} * t_{\text{Exposure}}$	0.0226	0.881
$T_{\text{Test}}^2 * t_{\text{Exposure}}$	0.000490	0.982
$T_{\text{Test}} * T_{\text{Exposure}}$	0.00269	0.959

The models describe the response of yield and ultimate tensile strengths very well ($R^2 \geq 0.995$). In both cases, the strength is dependent on the test temperature, the test temperature squared, and the exposure temperature. The exposure time did not enter into the models. The last result is somewhat in contradiction to the analysis of the strength at each test temperature as a function of exposure time. This is likely a reflection of the poor fit of the regression curves for several of the individual cases. Examining Figures 9(a) and (b), one could also argue that there is a change in the strength between as-received and 1000 h exposures, but little or no change for longer exposures. This is consistent with the models developed as well. Examination of the terms containing t_{Exposure} do indicate that their *F* values are fairly high in some cases, but they are all clearly not high enough to consider forcing terms with t_{Exposure} into the models.

The elongation shows a dependency on the test temperature squared. There is also an interaction between the test temperature squared and the exposure temperature that is statistically significant. No other independent variable entered the model. The overall fit of the regression model is poorer than for the strength models as demonstrated by the R^2 value of only 0.649. Examination of the data shows that there is more scatter in the elongation results, so the lesser fit for the elongation data was not unexpected. It is also typical to see more scatter for elongations than for strength data, so these data are not inconsistent with most tensile test data. The model is likely a reasonable representation of the mean of the elongation that will be observed over the ranges of the independent variables tested, so it was accepted.

Confidence intervals for the model values can be estimated as well. The general form of the equation for an estimate of the confidence interval is

$$Y_{CI}(T_{\text{Test}}, T_{\text{Exposure}}, t_{\text{Exposure}}) = f(T_{\text{Test}}, T_{\text{Exposure}}, t_{\text{Exposure}}) \pm t(1-\alpha, \nu)\, S_{Y.X} \tag{4}$$

where $Y_{CI}(T_{\text{Test}}, T_{\text{Exposure}}, t_{\text{Exposure}})$ is the approximate $(1 - \alpha)100\%$ confidence interval for a future model prediction for property Y; $f(T_{\text{Test}}, T_{\text{Exposure}}, t_{\text{Exposure}})$ is the resultant regression equation for prediction of the property Y; $t(1 - \alpha,\nu)$ is the Student t value for a given confidence $(1 - \alpha)$ and degrees of freedom (ν); and $S_{Y.X}$ is the standard error of the regression.

The standard error of estimate for each model are given in Tables XII to XIV. Substituting Equation (3) for $f(T_{\text{Test}}, T_{\text{Exposure}}, t_{\text{Exposure}})$ and the appropriate regression coefficient values into Equation (4) yields the following three equations:

$$\sigma_{\text{Yield}}(T_{\text{Test}}, T_{\text{Exposure}}, t_{\text{Exposure}}) = 1029 - 2.897T_{\text{Test}} + 2.29\times10^{-3}T_{\text{Test}}^2 - 0.0296T_{\text{Exposure}} \pm 8.611t(1-\alpha, 151) \tag{5}$$

$$\sigma_{UTS}(T_{\text{Test}}, T_{\text{Exposure}}, t_{\text{Exposure}}) = 1045 - 2.580T_{\text{Test}} + 1.90\times10^{-3}T_{\text{Test}}^2 - 0.0325T_{\text{Exposure}} \pm 8.471t(1-\alpha, 152) \tag{6}$$

$$\text{Elongation}(T_{\text{Test}}, T_{\text{Exposure}}, t_{\text{Exposure}}) = 40.72 - 6.20\times10^{-5}T_{\text{Test}}^2 + 7.31\times10^{-8}T_{\text{Test}}^2 T_{\text{Exposure}} \pm 3.190t(1-\alpha, 151) \tag{7}$$

One- and two-sided confidence intervals can be constructed by selecting the appropriate values of α and $t(1 - \alpha,\nu)$. Equations (5) to (7) can also be used in finite element analyses and other analysis of the properties of CP Ti between 298 and 650 K (77 and 711 °F) for as-received and thermally exposed material.

Discussion

The data indicate that the tensile properties of CP Ti Grade 2 are dependent to varying degrees upon the three independent variables examined: exposure temperature, exposure time, and tensile test temperature. The relative magnitude of these dependencies and their implications on future designs will be explored. In addition, the limitations of the current data models will be examined, and the current data set will be compared with literature data.

Effect of Thermal Exposure on Tensile Properties

As with the room temperature tensile properties, statistically significant differences in most tensile properties were discerned between the various thermal exposures at each elevated test temperature. These differences tend to be small.

Overall, the effects of thermal exposure on elevated-temperature properties are minimal as shown by the combined models. In the case of 0.2% offset yield and ultimate tensile strengths, the combined model indicates that a change in the exposure temperature of 100 K (180 °F) changes the strength by less than 5 MPa (0.7 ksi), and there is no effect of exposure time. For all practical engineering purposes, there is no effect of thermal exposure on the strength of CP Ti Grade 2.

The same holds true of the elongation. The exposure temperature did enter into the model, but the effect of a 100 K change in thermal exposure temperature is on the order of a change in the elongation value of 0.01 percent. Again, for all practical engineering purposes, the thermal exposure has no effect.

There had been some indications that exposure time and exposure temperature might have some small effect based upon the regression analyses performed on each independent variable individually. The R^2 values for the regression analyses of the strength versus exposure time for some conditions exceeded 0.6.

However, many other R^2 values were well below 0.25. With one exception, the elongation regressions had R^2 values below 0.4. Taken as a whole, the individual regressions do not support any effect of exposure time on the tensile properties of CP Ti Grade 2. The lack of corresponding terms in the accepted models was therefore a reasonable conclusion.

The comparison of the difference in the tensile properties for material exposed at 550 K (531 °F) versus that exposed at 650 K (711 °F) for the same length of time that was tested at the same temperature graphically did show that there were differences that could be substantial, especially at 650 K. The appearance of terms including the exposure temperature (T_{Exposure}) in all three models is consistent with the observations. The magnitude of the effect is small as shown by the small coefficients for the appropriate terms, so the overall effect, while measurable and quantifiable, is negligible and can generally be ignored.

Effect of Test Temperature on Tensile Properties

The independent variable affecting the tensile properties the most is clearly the test temperature. This was not unexpected since most materials exhibit a decrease in tensile strength as the test temperature is increased. The data allowed the development of models for 0.2% offset yield strength, ultimate tensile strength, and elongation that captured this dependency. Since only three test temperatures are available, the models were limited in complexity to a second-order polynomial for the test temperature dependence. Testing at additional temperatures can help refine this dependency if needed.

As shown in Equations (4) to (6), the models can also be expanded to give lower confidence limits for the properties using the standard error of the estimate ($S_{Y.X}$) multiplied by the appropriate Student t value. This will be useful for design analyses where parts are likely to be designed to a lower limit rather than the mean values.

Because almost all of the change in properties occurs because of a change in the test temperature, there is an implication that most of the changes that will be seen in an application can be captured by testing as-received material at the temperature of interest. This eliminates the need for expensive and time consuming testing of thermally exposed specimens except as a check for the most critical applications.

Limitations of the Models

It should be mentioned that the models developed here were all done for a single sheet of CP Ti Grade 2. A second sheet of CP Ti Grade 2 would likely have slightly different tensile properties. Most likely their results would be offset some amount higher or lower than the current test results. For a more universal model, true repeats with specimens coming from different sheets made from different starting stock would be required.

The trends of the current model are likely correct. The magnitudes may change somewhat, but not likely dramatically, if more specimens representing true repeats are added to the data sets. As such, the models still provide good guidance for the average and minimum properties that can be expected from thermally exposed CP Ti Grade 2.

Comparison With Literature Data

Limited literature data are available for elevated-temperature tensile properties of CP Ti Grades 1 and 2. Minimum values (Refs. 2 and 3) rather than averages are presented in Tables I and II. The grain size and confidence level for the minimums from the literature are also unknown. To compare the literature values to the current work, the models (Eqs. (5) to (7)) were used to generate a lower 95% confidence interval for the strength and elongation with the results shown in Figure 13. In the models, T_{Exposure} was set to 298 K (77 °F) since the literature data is for the equivalent of as-received sheet.

Looking first at the data from the current study versus the lower confidence limit for the models, the yield data set (Fig. 13 (a)) has a few data points below the line representing the 95% lower confidence limit. This is expected for a large data set (151 total data points for the model and 49 data points for as-received specimens). For a 95% confidence limit, about eight data points from the data used to generate the model should fall below the 95% confidence limit. For the ultimate tensile strength (Fig. 13(b)), there is only one data point from the as-received data below the 95% lower confidence limit. The as-received elongation data (Fig. 13(c)) also have one data point below the lower 95% confidence limit. These results are consistent with expectations and indicate that the models are presenting reasonable lower confidence limits for the current data set.

The current material has a chemistry that meets the chemical requirements of CP Ti Grade 1. Compared with the literature values for CP Ti Grade 1, the lower confidence interval for the current material's yield strength (Fig. 13(a)) exceeds the minimum strength values from the literature at all temperatures. The values for the two lower curves approach each other when the test temperature is at or above 550 K (531 °F). Based upon the regression line of the CP Ti Grade 1 literature data, the two values would be essentially identical at 650 K (711 °F). The ultimate tensile strength (Fig. 13(b)) shows a similar convergence around 550 K, but the literature values for the ultimate tensile strength show a larger decrease at 589 K (601 °F) than that seen with the current data set and the model. The values are still quite similar and likely not sufficiently different to indicate that the two data sets are greatly dissimilar. From this it appears that the current material's tensile strength is quite similar to CP Ti Grade 1, based upon the literature data.

As is shown in Figure 13(c), the 95% lower confidence limit for the elongation of the material tested in this study is less than that of the literature minimum values for CP Ti Grade 1 over most of the temperature range tested. Examining the data points for the as-received specimens tested in this study, they generally are above the regression line for the literature minimum values. The large variability of the elongation increases the value of the standard estimate of error ($S_{Y.X}$). This increases the value that is subtracted from the model's prediction of the value of the elongation, and these large values are likely to account for most of the difference between the literature and model minimums. It is unclear if the lower elongation predicted by the model of the current data would represent an issue in the design of a component. The predicted elongation does remain fairly high, and all test data exceeds 15 percent elongation over the entire temperature range tested.

The current material was produced as CP Ti Grade 2, and it has the corresponding strength advantage over CP Ti Grade 1 at room temperature. Figure 13(a) shows that the 95% lower confidence interval exceeds the regression line for the CP Ti Grade 2 literature minimum values up to ~525 K (486 °F). At higher temperatures, the lower confidence limit is less than the literature CP Ti Grade 2 regression line. Even many of the data points fall below the literature regression line. The difference between the model and the literature is about 15 MPa (2.2 ksi). Similar results are seen for the ultimate tensile strength (Fig. 13(b)) with the model's 95% lower confidence limit exceeding the regression line for the literature CP Ti Grade 2 minimum values up to about 500 K (441 °F). At higher temperatures the CP Ti Grade 2 literature regression line exceeds the model lower confidence limit by up to 30 MPa (4.3 ksi) at 650 K (711 °F).

The elongation 95% lower confidence limit for the current study shown in Figure 13(c) again falls below the regression line for the literature elongation minimum values. As with the CP Ti Grade 1, most of the individual data points are above the regression line. It is again believed that the variability of the data and corresponding $S_{Y.X}$ value leads to the lower values for the model.

All three lines for the elongation in Figure 13(c)—95% lower confidence limit, CP Ti Grade 1, and CP Ti Grade 2 minimum values—tend to coincide around room temperature (298 K, or 77 °F) and 650 to 700 K (711 to 801 °F). The data for the current study is also consistent with the shape of the literature value regression lines. It is suspected that the selection of 550 K (531 °F) as the lower elevated temperature rather than a temperature closer to 475 K (396 °F) (the approximate average of room temperature and 650 K, or 711 °F) may have resulted in the model missing a peak in the elongation between 298 and 550 K, which is indicated by the literature data. There may also be an increase in the elongation at temperatures above 650 K not seen by the model due to test temperature limitations. This supposition is based upon the CP Ti Grade 2 literature data. It is felt that the model is still a reasonably

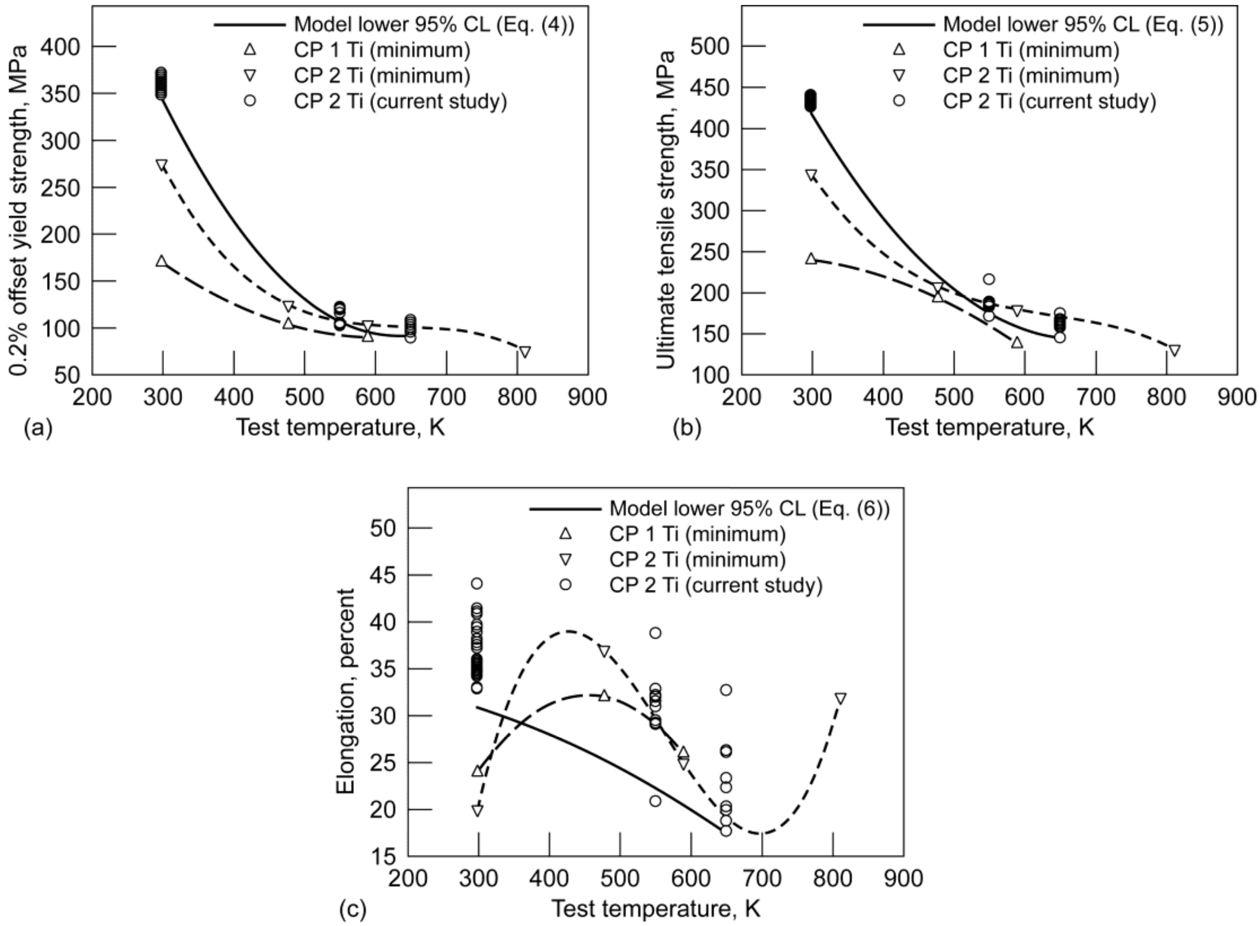

Figure 13.—Comparison of model lower 95% confidence limits (CL) for as-received CP Ti Grade 2 and literature minimum values for CP Ti Grade 1 and Grade 2 (Refs. 2 and 3). (a) 0.2% Offset yield strength. (b) Ultimate tensile strength. (c) Elongation.

accurate representation of the elongation of the material tested in the study and that the data are consistent with the literature results. The model gives a conservative lower confidence limit, and the lower limit values between 298 and 550 K should be lower than would be seen if the specimens had been tested at intermediate temperatures within this range. These are not necessarily unacceptable, but designers should be aware that it is likely that the ductility as measured by elongation is higher at the intermediate temperatures and use of the model will give perhaps overly conservative results. It may be better to substitute the minimum elongation for CP Ti Grade 1 or perhaps Grade 2 between 298 and 550 K.

From the strength plots, it appears that the low-temperature behavior of the current material is more consistent with CP Ti Grade 2. At higher temperatures above about 500 K, the current Ti sheet is more consistent with CP Ti Grade 1. The elongation data is more ambiguous because of the shape of the regression curves and the temperatures selected. Either CP Ti Grade 1 or Grade 2 could be similar to the material in the current study.

At elevated temperatures, the strength is likely more controlled by the chemistry of the material. The lower concentration of interstitial elements such as O in the material that was tested than can be found in material that meets the composition of CP Ti Grade 2 would tend to result in less pinning of dislocations and easier dislocation movement in the study material. This would tend to lower the macroscopic stress of the tested specimens to values more consistent with CP Ti Grade 1. Based upon this, it is felt that the composition is the major controlling factor above 500 K.

It should be noted that the differences in strengths above 500 K for all three data sets fall within 50 MPa (7.2 ksi) of each other, even for the worst case. The significance of the differences for engineering purposes where fairly large factors of safety are applied to lower confidence limit values is unclear. It may be that literature minimum values for either CP Ti Grade 1 or Grade 2 can substitute for actual data in this temperature range. Much will depend upon the criticality of the strength to the design.

Most importantly, the models developed for the thermally exposed CP Ti Grade 2 do not show gross discrepancies in the strength data, but there were understandable differences in the elongation data when compared with the available literature values. This indicates that literature data from similarly processed CP Ti Grade 2 sheets with CP Ti Grade 1 compositions likely can be used to supplement and refine the model.

Implications for Design of Extended Life Power Systems

Based upon these results, the tensile properties of CP Ti Grades 1 and 2 exposed for up to 5000 h at temperature between 298 and 650 K (77 and 711 °F) can be well characterized by tests of as-received material. The effects of the thermal exposure measured in some cases were small enough that they generally fall within the typical scatter of the data. For critical conditions, options exist on how to handle the small observed differences. The model developed for the exposed material can be used to calculate the change in properties, a small increase in safety factor can be incorporated into the design, or the lower confidence interval can be changed from 95 percent to a higher confidence level such as 99 percent.

In general, designers will not have to worry about the effects of thermal exposure, just the effects of operating temperature.

Summary and Conclusions

Commercially pure titanium (CP Ti) Grade 2 was tensile tested at 550 and 650 K (531 and 711 °F) following thermal exposures lasting up to 5000 h. Some statistically significant differences were noted using a combination of one-way ANOVA and Student-Neumann-Keuls analyses or Kruskal-Wallis one-way analysis of variance on ranks and Dunn’s analysis as was appropriate. The differences were generally small and likely have minimal practical significance for engineering applications.

The data were combined with previous room temperature test data, and forward stepwise regression analyses were conducted on the three independent variables in the study (test temperature, thermal exposure temperature, and thermal exposure time) to develop a combined model with confidence intervals for each of the dependent variables (0.2% offset yield strength, ultimate tensile strength, and elongation). The results showed that the test temperature was by far the most important independent variable. The thermal exposure temperature also makes a minor contribution. Thermal exposure time did not have a statistically significant effect on any of the tensile properties.

Based upon these results, thermal exposure has a very minimal effect on the strength and ductility of CP Ti Grade 2 over the range of test conditions used in this study. The material used in this study meets the chemistry requirements for CP Grade 1 Ti, so it is likely that the same conclusion can be reached for that grade as well.

The general lack of changes in tensile properties with thermal exposure indicates the CP Ti Grade 2 is stable and likely can be used in power generation applications where it may see usage for several years. Since test or usage temperature dominates the tensile properties so much, testing of as-received material at the temperatures of interest up to 650 K (711 °F) should be sufficient in most cases with little or no need to conduct thermal exposures. This will simplify the design process and lower costs by eliminating testing.

Future Work

The results of this study and the room temperature tensile testing will be compared with the tensile properties of CP Ti Grade 2 samples taken from the same sheet and exposed at 550 and 650 K (531 and 711 °F) in a liquid NaK environment when those data are available. The exposure time for those specimens will exceed 10,000 h. Those samples in the NaK study not exposed to NaK as a control will provide data that can be added to this work for additional analysis. The tensile strength of samples exposed to NaK will be compared with the final data set to determine if thermal exposure or NaK exposure resulted in any statistically significant changes in the tensile properties of CP Ti Grade 2 at the temperatures of interest.

References

1. Breden, C.R., et al.: Water Corrosion of Structural Materials; October 1948–June 1951. Argonne National Laboratory ANL–4519, 1951.
2. Standard Specification for Titanium and Titanium Alloy Strip, Sheet, and Plate. ASTM Book of Standards, ASTM B265–08, vol. 02.04, 2006.
3. Titanium Alloy Guide. RMI brochure, RMI Titanium Company, Niles, OH, 2000, pp. 18–19. http://rtiintl.s3.amazonaws.com/RTI-Reports/tiguideWeb.pdf Accessed Nov. 16, 2011.
4. Loewenthal, W.S., et al.: Compatibility of Titanium With Liquid Metal NaK (78 wt% Potassium/22 wt% Sodium) Evaluated. HITEMP Review 2006, NASA/TM—2007-214479, pp. 200–202.
5. Ellis, David L.: Effects of Long Term Thermal Exposure on Chemically Pure (CP) Titanium Grade 2 Room Temperature Tensile Properties and Microstructure. NASA/TM—2007-214968, 2007.
6. Paton, N.E.; and Backofen, W.A.: Plastic Deformation of Titanium at Elevated Temperatures. Met. Trans. B, vol. 1, no. 10, 1970, pp. 2839–2847.
7. Chakravarti, I.M.; Laha, R.G.; and Roy, J.: Handbook of Methods of Applied Statistics. Vol. I, John Wiley & Sons, 1967, pp. 392–394.

Appendix A

Results of Room Temperature Tensile Tests

Table XV gives all results from prior room temperature tensile testing. It also contains statistical analysis for each heat treatment condition. The as-received samples were cut using either a water jet or wire electrical discharge machining.

TABLE XV.—ROOM-TEMPERATURE TENSILE TESTING RESULTS FOR CP Ti GRADE 2

(a) As received

Sample	Yield strength, MPa	Ultimate tensile strength, MPa	Elongation, percent
Water-jet machined			
RT–1A[a]	329.7	463.2	33.0
RT–1B	363.5	427.4	32.8
RT–1C	362.5	434.0	35.0
RT–1D[a]	327.8	462.0	33.8
RT–1E	352.8	439.7	35.4
RT–1F	351.7	432.2	35.6
RT–1G	370.7	437.1	41.4
RT–1H	363.1	435.3	34.1
RT–1I	347.9	433.9	40.7
RT–1J	352.6	434.5	44.0
RT–1K	356.6	432.1	39.4
RT–1L	360.9	434.3	34.7
RT–1M	354.3	431.0	37.1
RT–1N	360.3	433.5	34.9
RT–1O	367.0	434.1	36.0
RT–1P	351.1	439.4	37.8
RT–1Q	371.8	440.2	37.1
RT–1R	370.0	438.8	37.4
RT–1S	347.5	438.1	38.8
RT–1T	367.0	437.5	39.7
RT–1U	369.6	435.9	35.8
RT–1V	360.8	430.5	34.2
RT–1W	361.0	432.9	41.0
RT–1X	367.3	439.6	33.0
Average	360.5	435.1	37.1
Standard deviation	7.6	3.4	3.0
One-sided 95% interval	3.9	1.8	1.5

[a]Outlier.

Sample	Yield strength, MPa	Ultimate tensile strength, MPa	Elongation, percent
Electrical discharge machined			
RT–2A	355.3	425.0	35.7
RT–2B	354.9	427.4	38.2
RT–2C	358.1	432.5	37.7
RT–2D	359.5	429.4	38.9
RT–2E	358.5	430.7	37.6
Average	357.2	429.0	37.6
Standard deviation	2.0	2.9	1.2
One-sided 95% interval	3.2	4.6	1.9

TABLE XV.—ROOM-TEMPERATURE TENSILE TESTING RESULTS FOR CP Ti GRADE 2

(b) Exposed at 550 K

Sample	Yield strength, MPa	Ultimate tensile strength, MPa	Elongation, percent
1000 h			
RT–3A	356.0	428.3	32.5
RT–3B	357.6	429.3	34.0
RT–3C	355.2	415.7	32.8
RT–3D	357.7	428.7	32.9
RT–3E[b]			
Average	356.6	425.5	33.1
Standard deviation	1.2	6.5	0.7
One-sided 95% interval	2.6	13.7	1.4
2000 h			
RT–5A	347.1	418.3	38.4
RT–5B	359.3	432.1	40.7
RT–5C	357.8	429.9	37.4
RT–5D	359.9	432.6	42.3
RT–5E	357.2	429.6	39.4
Average	356.3	428.5	39.6
Standard deviation	5.2	5.9	1.9
One-sided 95% interval	8.2	9.2	3.0
3000 h			
RT–7A	346.1	426.1	33.5
RT–7B	350.0	427.4	34.5
RT–7C	344.9	425.9	33.0
RT–7D	345.2	429.6	33.6
RT–7E	350.4	429.1	32.8
Average	360.5	435.1	37.1
Standard deviation	7.6	3.4	3.0
One-sided 95% interval	3.9	1.8	1.5

[b]Missing specimen.

Sample	Yield strength, MPa	Ultimate tensile strength, MPa	Elongation, percent
4000 h			
RT–9A	359.1	431.3	43.0
RT–9B	354.8	425.4	42.5
RT–9C	355.5	429.4	43.4
RT–9D	357.8	427.4	40.5
RT–9E	354.9	428.6	42.3
Average	356.4	428.4	42.3
Standard deviation	1.9	2.2	1.1
One-sided 95% interval	3.0	3.5	1.7
5000 h			
RT–11A	353.7	432.8	36.8
RT–11B	355.0	433.6	36.5
RT–11C	351.1	431.2	35.5
RT–11D	329.6	411.1	35.8
RT–11E	353.1	428.1	37.6
Average	348.5	427.4	36.4
Standard deviation	10.7	9.3	0.8
One-sided 95% interval	16.7	14.6	1.3

TABLE XV.—ROOM-TEMPERATURE TENSILE TESTING RESULTS FOR CP Ti GRADE 2

(c) Exposed at 650 K

Sample	Yield strength, MPa	Ultimate tensile strength, MPa	Elongation, percent
1000 h			
RT–4A	355.4	427.5	37.8
RT–4B	355.3	425.9	42.0
RT–4C	353.8	426.0	43.1
RT–4D	356.3	426.5	44.7
RT–4E	352.3	427.4	43.0
Average	354.6	426.7	42.1
Standard deviation	1.6	0.7	2.6
One-sided 95% interval	2.4	1.2	4.1
2000 h			
RT–6A1	351.8	424.9	39.1
RT–6B	351.2	423.5	38.3
RT–6C	350.4	425.6	39.6
RT–6D	349.4	423.7	36.0
RT–6E	351.3	424.1	35.4
Average	350.8	424.4	37.7
Standard deviation	0.9	0.9	1.9
One-sided 95% interval	1.5	1.4	2.9
3000 h			
RT–8A	345.6	420.0	40.2
RT–8B	348.7	423.1	38.8
RT–8C	348.9	423.6	41.6
RT–8D	346.7	423.7	40.6
RT–8E	351.0	424.0	39.6
Average	348.2	422.9	40.2
Standard deviation	2.1	1.7	1.1
One-sided 95% interval	3.3	2.6	1.6

Sample	Yield strength, MPa	Ultimate tensile strength, MPa	Elongation, percent
4000 h			
RT–10A	351.3	424.1	40.5
RT–10B	349.1	421.6	41.3
RT–10C	351.2	424.6	41.8
RT–10D	348.8	420.0	40.8
RT–10E	352.0	422.7	39.8
Average	350.5	422.6	40.8
Standard deviation	1.4	1.9	0.8
One-sided 95% interval	2.2	2.9	1.2
5000 h			
RT–12A	343.4	419.0	41.3
RT–12B	342.2	418.1	47.6
RT–12C	343.3	420.3	44.5
RT–12D	346.5	422.0	44.3
RT–12E	343.8	418.3	43.2
Average	343.8	419.5	44.2
Standard deviation	1.6	1.6	2.3
One-sided 95% interval	2.5	2.6	3.6

Appendix B

Regression Analysis of Strength as a Function of Testing Temperature

Figure 14 shows the data and regression curves for the effect of temperature upon the strength of CP Ti Grade 2 following long-term thermal exposures. The regression curve coefficients are found in Table VIII.

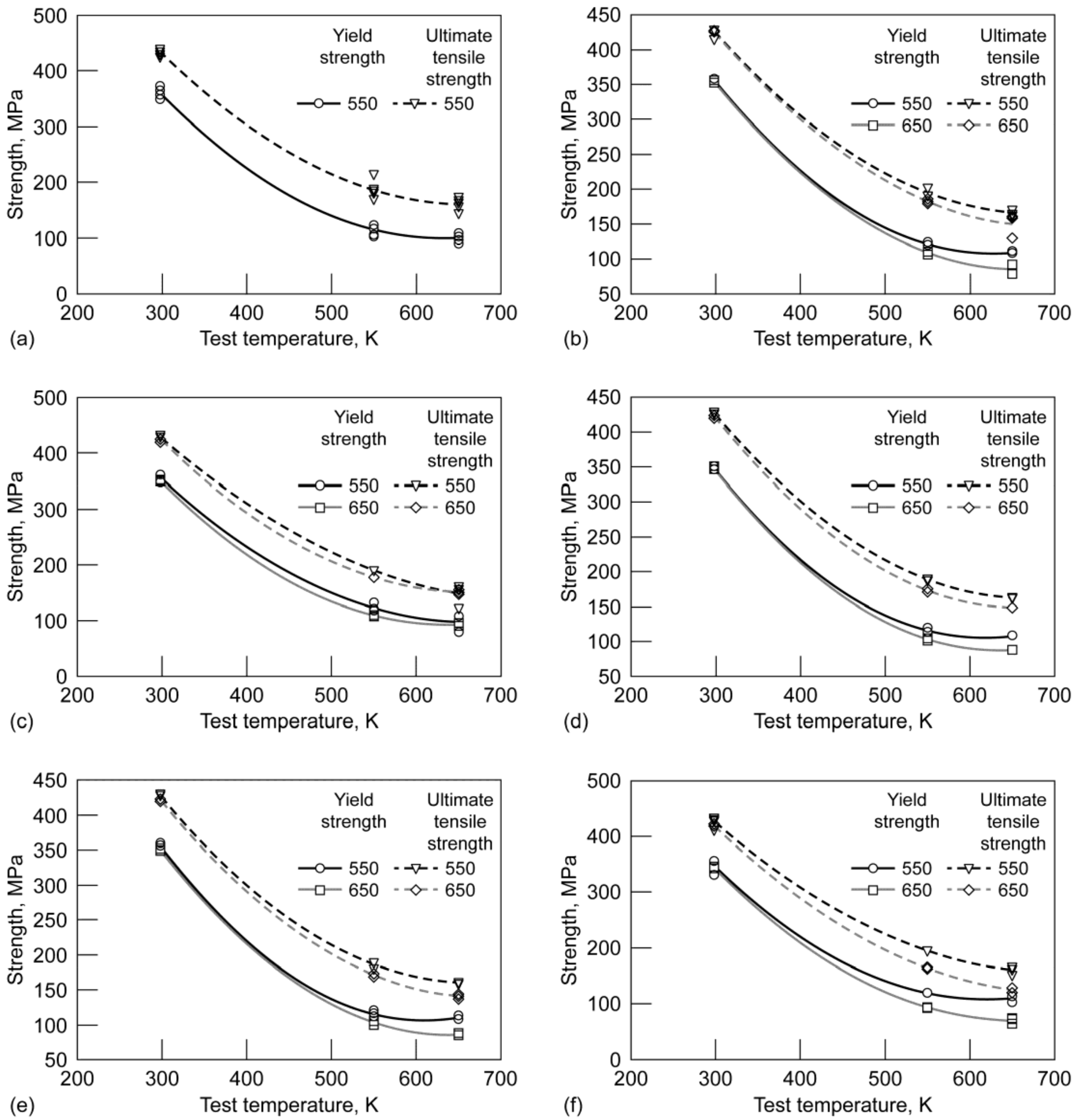

Figure 14.—0.2% offset yield strength and ultimate tensile strength as function of test temperature for CP Ti Grade 2 both as received and exposed at 550 and 650 K for different times. (a) As received. (b) 1000 h exposure. (c) 2000 h exposure. (d) 3000 h exposure. (e) 4000 h exposure. (f) 5000 h exposure.

Appendix C

Regression Analysis of Elongation as a Function of Testing Temperature

Figure 15 shows the data and regression curves for the effect of temperature upon the elongation of CP Ti Grade 2 following long-term thermal exposures. The regression curve coefficients are found in Table X.

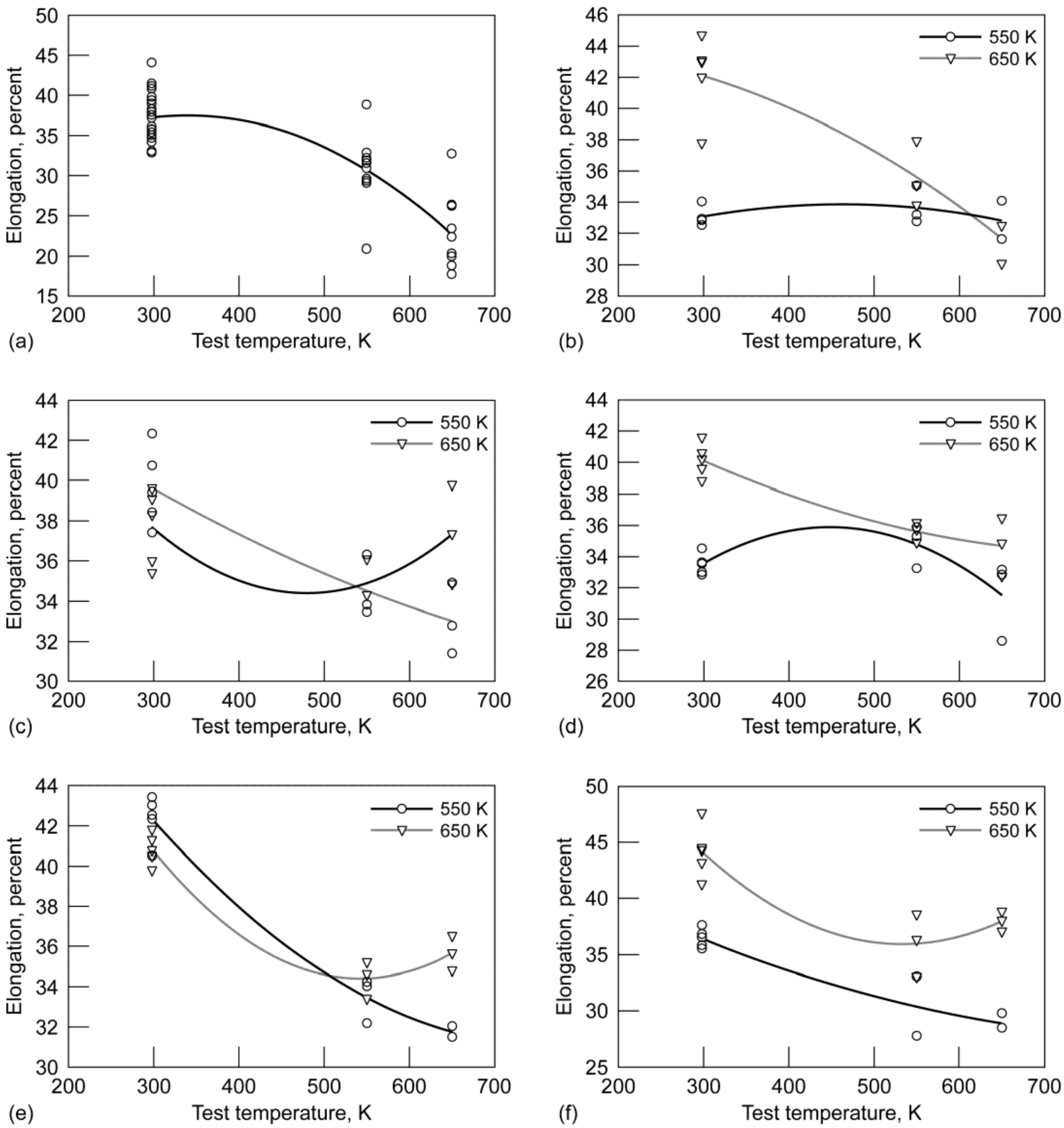

Figure 15.—Elongation as function of test temperature for CP Ti Grade 2 both as received and at 550 and 650 K exposure temperatures for different times. (a) As received. (b) 1000 h exposure. (c) 2000 h exposure. (d) 3000 h exposure. (e) 4000 h exposure. (f) 5000 h exposure.

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*
01-12-2012

2. REPORT TYPE
Technical Memorandum

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Effects of Long-Term Thermal Exposure on Commercially Pure Titanium Grade 2 Elevated-Temperature Tensile Properties

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Ellis, David, L.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
WBS 463169.04.03.05.05

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135-3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E-16688

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITOR'S ACRONYM(S)
NASA

11. SPONSORING/MONITORING REPORT NUMBER
NASA/TM-2012-215484

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Category: 26
Available electronically at http://www.sti.nasa.gov
This publication is available from the NASA Center for AeroSpace Information, 443-757-5802

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Elevated-temperature tensile testing of commercially pure titanium (CP Ti) Grade 2 was conducted for as-received commercially produced sheet and following thermal exposure at 550 and 650 K (531 and 711 °F) for times up to 5000 h. The tensile testing revealed some statistical differences between the 11 thermal treatments, but most thermal treatments were statistically equivalent. Previous data from room temperature tensile testing was combined with the new data to allow regression and development of mathematical models relating tensile properties to temperature and thermal exposure. The results indicate that thermal exposure temperature has a very small effect, whereas the thermal exposure duration has no statistically significant effects on the tensile properties. These results indicate that CP Ti Grade 2 will be thermally stable and suitable for long-duration space missions.

15. SUBJECT TERMS
Titanium; Thermal exposure; Tensile testing

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					STI Help Desk (email:help@sti.nasa.gov)
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(include area code)*
U	U	U	UU	46	443-757-5802