Effect of Creep in Titanium Alloy Ti-6Al-4V at Elevated Temperature on Aircraft Design and Flight Test

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INTRODUCTION

Studies which are directed toward predicting creep strains in built-up structures are critically dependent on adequate material characterization. Available literature (references 1 through 3) indicates large excursions in material behavior in coupon creep testing of titanium alloy Ti-6Al-4V. It is the purpose of this report to add to the data base by reporting the results of elevated temperature compressive creep tests on three coupons of this alloy and to relate this information to aircraft design and flight test. The three coupons were compressed at a temperature of 714K (825F°) and at three different stress levels ranging from 60.12 MPa (8720 lbs/in^2) to 104.45 MPa (15150 lbs/in^2). The creep strains resulting from the tests are compared to several known creep laws and the implications on aircraft design and flight testing are identified.

SYMBOLS

e	natural logarithm base of value 2.7183
ε_c	strain due to creep, μm/m (μin/in)
σ	stress, MPa (lbs/in^2)
t	time, hours
T	temperature, K (F°)

TEST PROCEDURE

Titanium Coupons

A photograph showing two of the titanium alloy Ti-6Al-4V coupons is presented in figure 1. The specimens were machined from .635 cm (.25 in) thick annealed sheet stock. The long axis of the specimen corresponds to the longitudinal axis of the sheet. The test section has the dimensions of .635 cm (.25 in) by 1.905 cm (.75 in). The overall length of the specimen is 13.970 cm (5.50 in). In order to maintain optimum buckling strength of the specimens, special end fixtures were machined to provide a fixed (zero rotation) end condition. One of the specimens is shown in the special fixture in the background of figure 1.

Instrumentation

The coupon instrumentation consisted of strain gages to measure the creep strain and thermocouples to determine specimen temperatures. Two high temperature weldable strain gages were mounted opposite each other on the two 1.905 cm (.75 in) faces near the center of the specimen. Chromel-alumel thermocouples were located on the surface of the specimen to control the radiant heating and to monitor the uniformity of the heating. The instrumentation can be seen in figure 1.

Several corrections were required to obtain valid data from the weldable strain gages utilized at elevated temperatures during the tests. After the strain gages were installed on the specimens, the specimens were heated slowly in an oven up to the test temperature several times so that apparent strain information was available for each of the strain gages. This information was used to correct the test data for apparent strain. The test data were also corrected for temperature induced gage factor changes for each of the strain gages as defined by the manufacturer.

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Heating and Loading

A sketch of the general test set-up is shown in figure 2. The loading system consisted of a loading bar on which dead weights were hung. The basic mechanical advantage of the lever was approximately four. The system was carefully constructed, fabricated, and positioned so that bending moments in the specimen were minimized. The special end fixtures shown in figure 1 were also required to provide fixed end conditions. This allowed a suitable specimen length to be used without danger of column buckling during the tests.

A radiant heating system was constructed around the test specimen as shown in figure 3. The temperatures were controlled with surface thermocouples associated with a closed loop system. The specimen was enclosed in a chamber with insulation so that an oven situation could be maintained as much as possible.

The basic test procedure consisted of slowly (approximately twenty minutes) heating the specimen from room temperature up to the test temperature of 714K (825F°). Once the test temperature was reached, it was held at that point for approximately thirty minutes to reach a near steady state temperature situation. At that time dead weights were added to the end of the loading bar to achieve at the specimen location a compressive force which would result in the desired stress in the specimen. The force and the heat were applied to the specimen for an excess of four hours. Three different specimens were tested at three different stress levels, but at identical temperatures. The first specimen was compressed at 60.12 MPa (8720 lbs/in^2), the second at 86.18 MPa (12500 lbs/in^2), and the third at 104.45 MPa (15150 lbs/in^2). All three specimens were compressed while at a test temperature of 714K (825F°).

RESULTS AND DISCUSSION

The results of the creep test are presented in figure 4. Cumulative creep strains one, two, three, and four hours after the onset of heating and loading are plotted on logarithmic scales for the three test specimens. The short duration of the test clearly limits the scope of the information to short term or primary creep. Although the creep test is of limited time duration, several creep laws were selected from available literature for comparison purposes.

Four different creep laws are presented in figure 4 for the titanium alloy Ti-6Al-4V tested in tension. Equation 1 was obtained from reference 1 and resulted from hand faired curves derived from test data:

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$$\ln \varepsilon_c = -24.09 + 22.54T + .0000006\sigma^2 + .905\ln\sigma + .433\ln t \qquad (1)$$

Equations 2, 3, and 4 were obtained from curve fitting exercises in reference 2. Equations 2, 3, and 4 are, respectively:

$$\varepsilon_c = 1.141\sigma^{.562}\, t^{.162}\, e^{(\frac{-3.45}{T})} \qquad (2)$$

$$\varepsilon_c = .6487\sigma^{.738}\, t^{.299}\, e^{(\frac{-4.21}{T})} \qquad (3)$$

$$\ln \varepsilon_c = -24.9 + 21.4T + 1.16\ln\sigma + .634\ln t + .0062(\ln t)^2 +$$

$$.000007\sigma^2 - .0332\,\frac{\ln\sigma\,\ln t}{T} \qquad (4)$$

It is apparent from examination of references 1 and 2 that many factors affect the rate of creep at elevated temperatures. This observation is further substantiated by examining reference 3. In addition to the three primary parameters, stress, temperature, and time, it is obvious that parameters such as material thickness, discrete lot, processing direction, and other factors clearly impact the results of characterization tests. The difficulties with curve fitting the inconsistent creep data of reference 2 is well substantiated when the standard errors of equations 2, 3, and 4 are examined. The standard error of the estimate for equations 2, 3, and 4, based on the natural logarithm of the strain are .6009, .6234, and .4360 respectively.

The lack of correlation of the test data of figure 4 with the four creep laws is not totally unexpected when the large variations among the creep laws is considered. It should be noted that extrapolations of the test data and the creep laws appears to result in a convergence at an estimated value of 1000 hours. It must also be remembered that the three coupons were tested in compression while all of the creep laws were developed from tensile tests. Nothing could be found in the literature to relate whether a given material creeps similarly in compression and tension at elevated temperature.

The most important single observation in this report must lie in the large excursions in short term (primary) creep implied by both the test data and the empirical creep laws of figure 4. This strongly

implies that short term creep is somewhat unpredictable. Aircraft events that result in extreme, but short term stress and temperature excursions must be approached cautiously. Deformations and/or residual stresses could quickly accumulate to intolerable values if predictive or monitorial capabilities are deficient for the short term effects. The apparent convergence of the creep data with the creep laws in the longer term situation (secondary creep) implies a much more predictable situation.
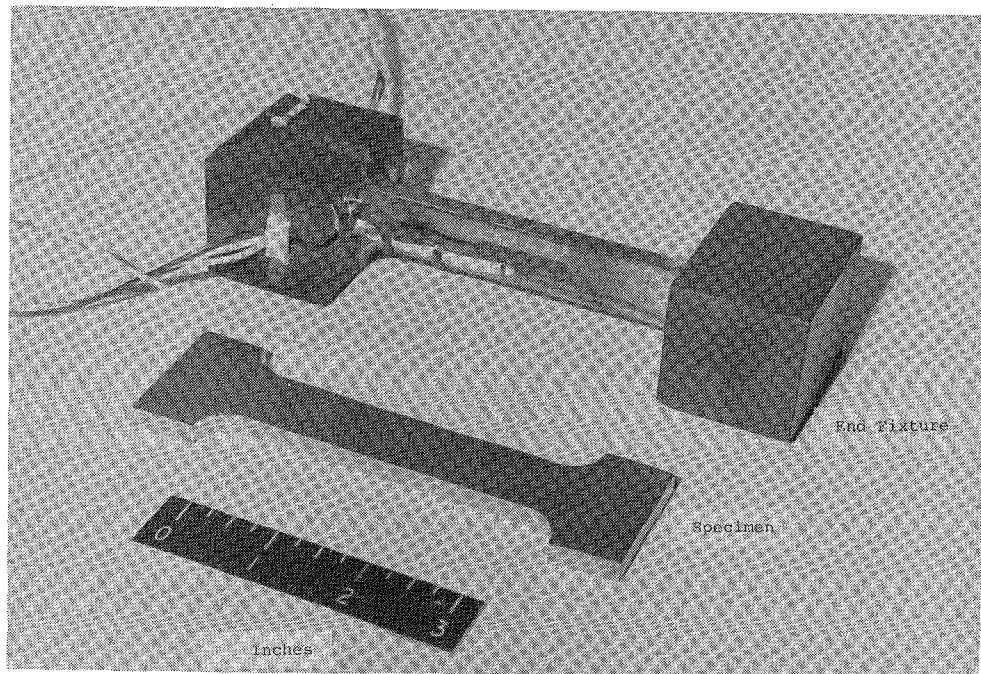
CONCLUDING REMARKS

Short-term compressive creep tests were conducted on three titanium alloy Ti-6Al-4V coupons at three different stress levels at a temperature of 714K (825F°). The test data were compared to several creep laws developed from tensile creep tests of available literature. The short term creep test data did not correlate well with any of the creep laws obtained from available literature. The creep laws obtained from available literature did not correlate well with each other either. Short-term creep does not appear to be very predictable for titanium alloy Ti-6Al-4V. Aircraft events that result in extreme, but short term temperature and stress excursions for this alloy should be approached cautiously. Extrapolations of test data and creep laws suggest a convergence toward predictability in the longer-term situation.

NASA Ames Research Center
  Dryden Flight Research Facility
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1. Davis, John W.; and Cramer, Bruce A.: Prediction and Verification of Creep Behavior in Metallic Materials and Components for the Space Shuttle Thermal Protection System. NASA CR-2685, July 1976.

2. Davis, J. W.; and Cramer, B. A.: Prediction and Verification of Creep Behavior in Metallic Materials and Components for the Space Shuttle Thermal Protection System. NASA-CR-132605-1, November 1974.

3. Blackburn, Linda B.: Creep Testing on Foil-Gage Metals at Elevated Temperature Using An Automated Data Acquisition System. NASA TM-84634, March 1983.

Figure 1.   Creep Specimens and Special End Fixtures.
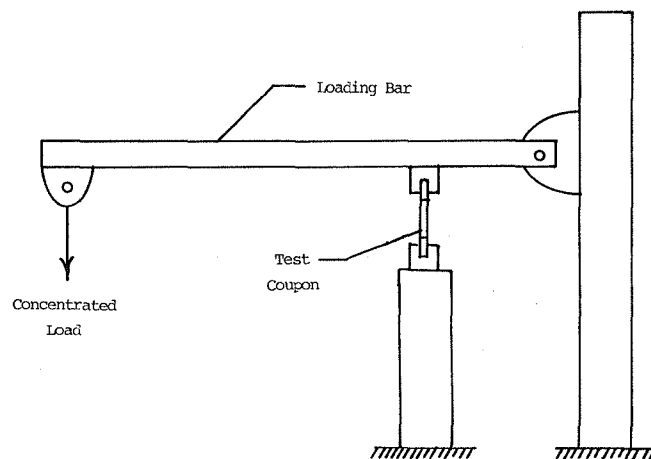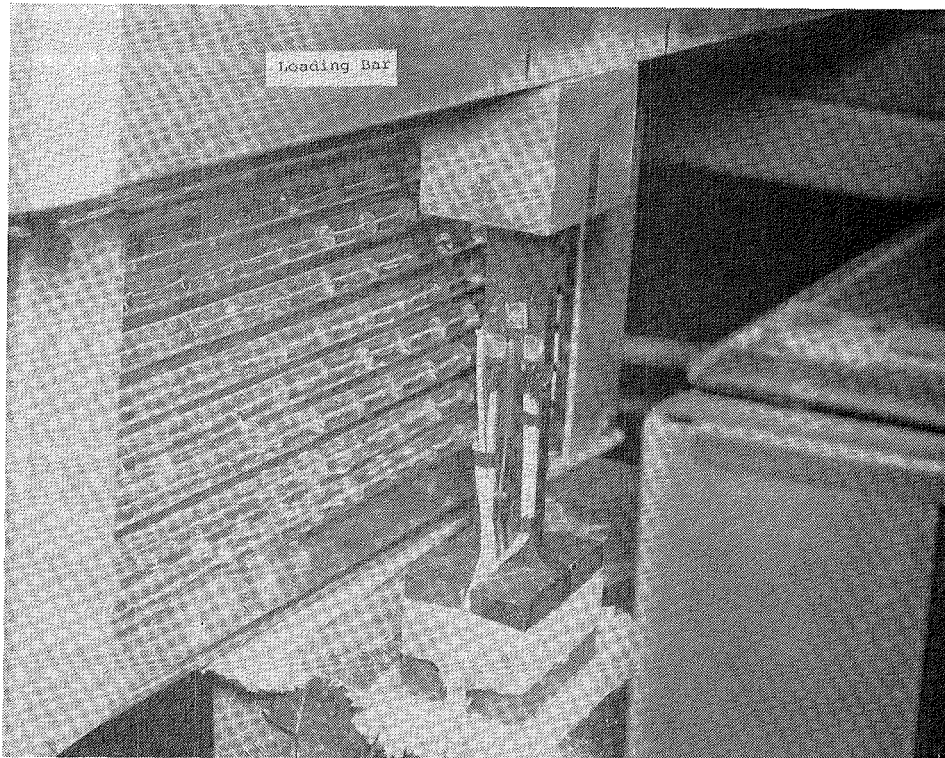

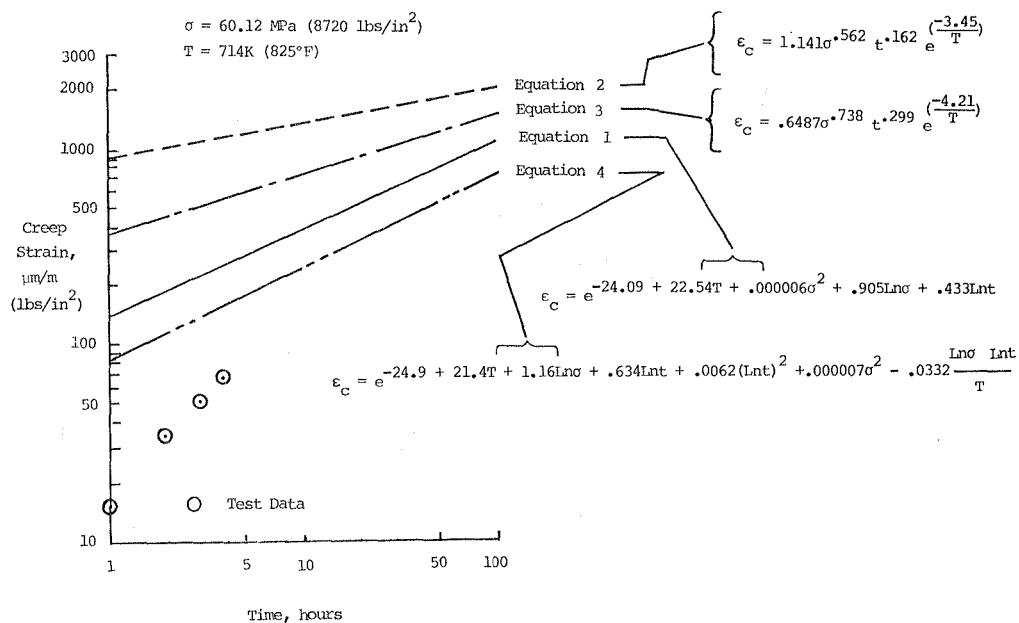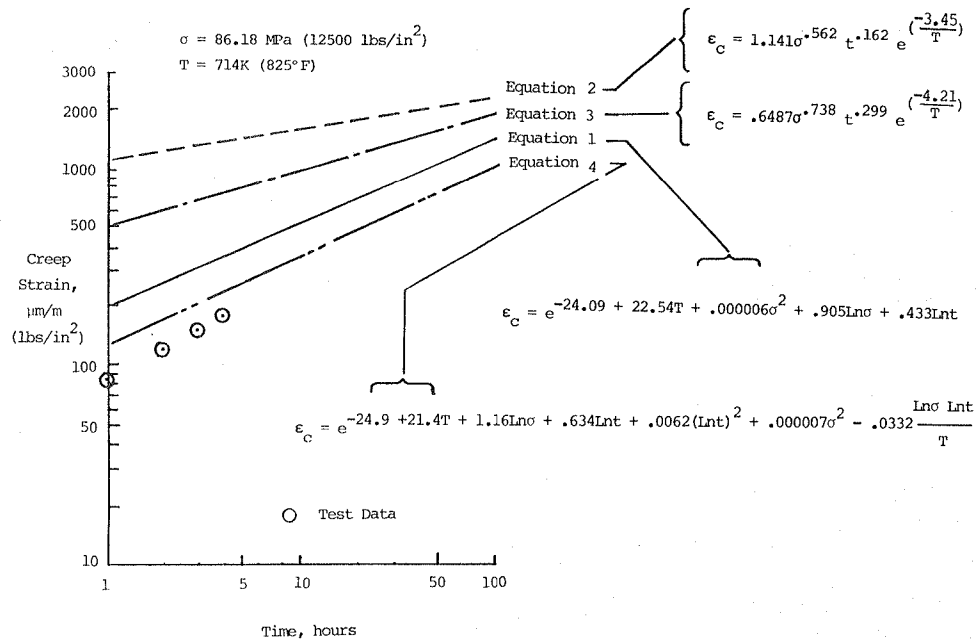Figure 2.   Sketch of General Test Set-Up.
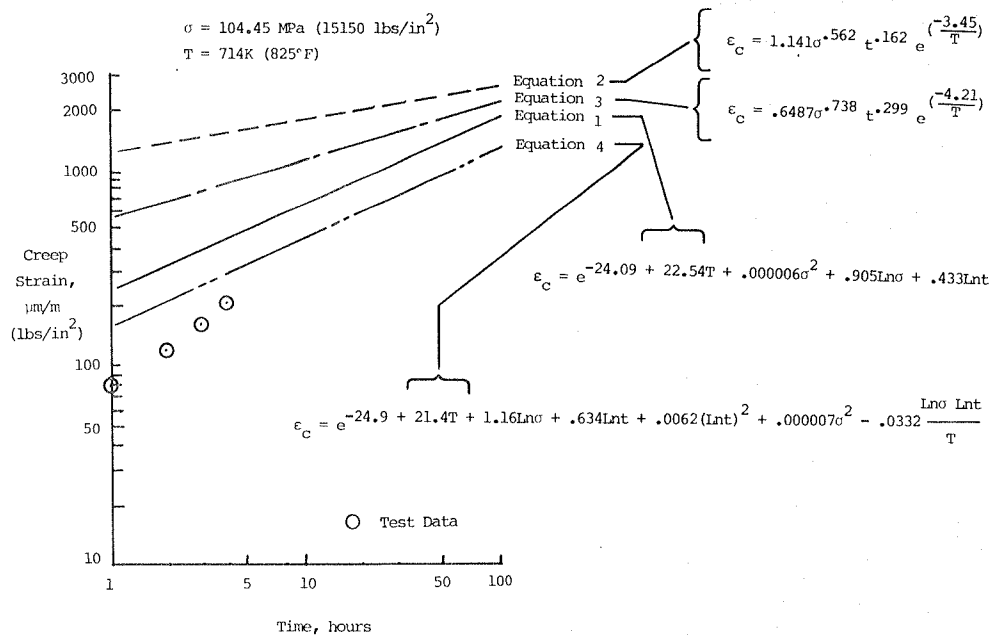
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Figure 3. Creep Specimen in the Test Fixture.

$\sigma = 60.12$ MPa (8720 lbs/in^2)
$T = 714$K (825°F)

Equation 2

$\varepsilon_c = 1.141\sigma^{.562} t^{.162} e^{(\frac{-3.45}{T})}$

Equation 3

$\varepsilon_c = .6487\sigma^{.738} t^{.299} e^{(\frac{-4.21}{T})}$

Equation 1

Equation 4

$\varepsilon_c = e^{-24.09 + 22.54T + .0000006\sigma^2 + .905Ln\sigma + .433Lnt}$

$\varepsilon_c = e^{-24.9 + 21.4T + 1.16Ln\sigma + .634Lnt + .0062(Lnt)^2 + .000007\sigma^2 - .0332\frac{Ln\sigma \ Lnt}{T}}$

O   Test Data

Time, hours

(a) Stress Equals 60.12 MPa (8720 lbs/in^2)

Figure 4. Comparison of Measured Creep Strains with Four Creep Laws.

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(b) Stress Equals 86.18 MPa (12500 lbs/in^2)

(c) Stress Equals 104.45 MPa (15150 lbs/in^2)

Figure 4. Concluded.

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15. Supplementary Notes

16. Abstract

Short-term compressive creep tests were conducted on three titanium alloy Ti-6Al-4V coupons at three different stress levels at a temperature of 714 K (825° F). The test data were compared to several creep laws developed from tensile creep tests of available literature. The short-term creep test data did not correlate well with any of the creep laws obtained from available literature. The creep laws themselves did not correlate well with each other. Short-term creep does not appear to be very predictable for titanium alloy Ti-6Al-4V. Aircraft events that result in extreme, but short-term temperature and stress excursions for this alloy should be approached cautiously. Extrapolations of test data and creep laws suggest a convergence toward predictability in the longer-term situation.

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