

# Creep Behavior of High Temperature Titanium Alloys at Low Stress-High Temperature Regime

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The application of titanium alloys at elevated temperature ranges from compressor disks/blades in aircraft jet engines to automotive exhaust systems. Near alpha titanium alloys such as Ti-6242S and TIMETAI.®834 (Ti-834) are the most notable titanium alloys for jet engine parts, where creep property at higher stress levels is one of the critical properties. One of disadvantages of near alpha titanium alloys is their poor formability that limits the applications where extensive cold forming and fabrication are required. Besides jet engines applications, there are certain applications that do not require higher stress but higher service temperatures are required. Notable applications include heat shields of aircrafts, sheets for thermal protection systems or jet engine exhaust and exhaust pipes/mufflers of automobiles. In this paper creep properties of two titanium alloys Ti-6242S and TIMETAI.®21S (Ti-21S), at elevated temperatures beyond 538°C were studied. Factors that control creep at low stress-high temperature regime are discussed.

**Keywords:** Titanium (Ti), Near alpha titanium alloy, Ti-6242S, Ti-21S, Creep behavior, Elevated temperature, Low Stress

## 1. Introduction

The search for alloys with improved high-temperature specific strength and creep-resistant properties for aerospace applications has led to sustained activities to develop new alloys and/or improve existing ones. A substantial part of these activities was devoted to titanium alloys and Ti aluminides, due to their high strength-to-weight ratio<sup>1,2</sup>. Titanium alloys are often used in applications wherein the combination of the exposure temperature and the applied stress necessitates consideration of creep<sup>3</sup>. Among various titanium alloys developed for high temperature applications, near alpha alloys such as Ti-6242S and Ti-834 are the most common alloys used for jet engine parts, where creep resistance at high stress level is one of the critical properties. In beta alloys, Ti-21S, which is strip produceable, is considered to be the best alloy for high temperature fabricated structure such as jet engine exhausts<sup>4</sup>. Certain other applications of high temperature titanium alloys such as heat shields of aircrafts, sheets for thermal protection systems and exhaust pipes/mufflers of automobiles also demand critical creep properties, but, at higher temperatures and lower stress levels.

Limited creep studies have been made to date on titanium alloys in this high temperature-low stress regime<sup>5</sup>. Therefore, an experimental investigation was undertaken to study the creep properties of the selected titanium alloys over a wide range of low stresses below 140MPa at an appropriate temperature range of 538°C to 704°C. An attempt was made in this paper, to understand and analyze the rate controlling mechanism influencing the creep properties of selected commercial titanium alloys in low stress-high temperature regime.

## 2. Experimental Procedure

### 2.1 Material and Specimen Fabrication

In the course of the present investigation, Ti-

6242S and Ti21S were selected. Duplex anneal, as shown in Table 1, was performed on the laboratory rolled 1.27mm thick sheet of Ti-6242S, (hereafter referred to as Ti-6242S ( $\alpha/\beta$ )). Earlier studies<sup>6,7</sup> have indicated that creep properties of Ti-6242S are largely dependent upon the microstructure. Therefore, Ti-6242S sheet in the beta-annealed condition (hereafter referred to as Ti-6242S ( $\beta$ )), was also produced and included in the present study.

The Ti-21S production sheet (1.27mm) was used in solution treat-duplex aged condition. The heat-treatments performed for the selected alloys are presented in Table 1.

**Table 1.** Standard heat treatment for the sheet materials used in this study

Alloy	Heat Treatment
Ti-21S	843°C/15min/AC, 690°C/8hr/AC, 649°C/8hr/AC
Ti-6242S ( $\alpha/\beta$ )	899°C/30min/AC, 788°C/15min/AC
Ti-6242S ( $\beta$ )	1052°C/30min/AC, 788°C/15min/AC

Following the heat treatment, standard creep samples with gage sections of 25.4mm in length and 1.27mm thick were fabricated from the sheets, according to ASTM E139.

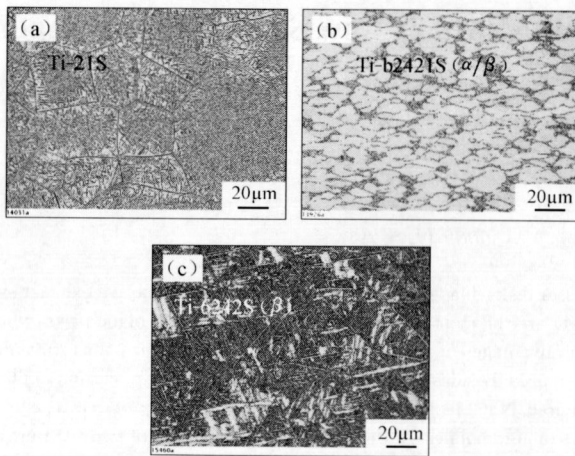
Chemical composition of these two alloys is shown in Table 2. Figure 1 presents optical micrographs showing the initial microstructure of the alloy sheets used in this study.

**Table 2.** Chemical composition of titanium alloys used for this study, (in weight percent)

Alloy	Al	Mo	Fe	Nb	Sn	Zr	Si	O
Ti-21S	2.84	15.5	0.28	2.71	—	—	0.20	0.12
Ti-6242S	6.15	1.99	0.04	—	1.99	4.19	0.09	0.19

### 2.2 Creep Testing

Most of the creep testing was performed at TIMET-Henderson Technical Laboratory, on ATS Series 2330 lever arm tester having a calibrated lever arm ratio of 3 : 1. Creep strain for all tests was continuously



**Figure 1.** Initial microstructure of titanium alloy sheets used for creep testing

measured using linear variable displacement transducers (LVDTs) that are interfaced with a computer controlled data acquisition systems. All creep testing was performed in air in a three zone furnace allowing a temperature control of better than  $\pm 2^{\circ}\text{C}$  of the desired temperature. The temperature of the test sample was monitored by a thermocouple attached directly to the gage section of the sample.

Creep tests were performed over a temperature range 538-704°C at initial applied stress levels ranging from 17.2 to 138MPa. All creep tests performed were continued for a sufficiently long duration to record considerable steady state deformation, needed for the determination of steady state creep rate.

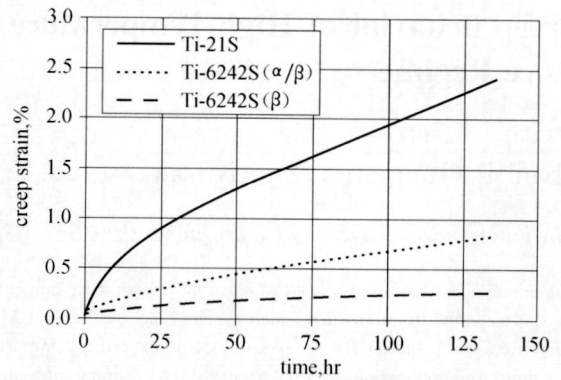
### 3. Results

#### 3.1 Creep Behavior and Test Results

Figure 2 shows the creep response of titanium alloys at 593°C and stress of 68.9MPa. The shape of the creep curve exhibits a normal primary creep region followed by steady state creep, which is the most common behavior observed during creep of metallic materials<sup>8)</sup>. The creep characteristics presented in Figure 2 are representative of all tests performed in this study. Table 3 presents results obtained from creep tests at selected conditions. It can be noticed that creep strain of Ti-21S at higher temperature and lower stress is superior to Ti-6242S ( $\alpha/\beta$ ). Ti-6242S ( $\beta$ ) has the superior properties compared to the other two materials at all test conditions.

**Table 3.** Creep test results of the selected titanium alloys at different temperatures and a stress of 34.5MPa showing % creep strain at various test durations

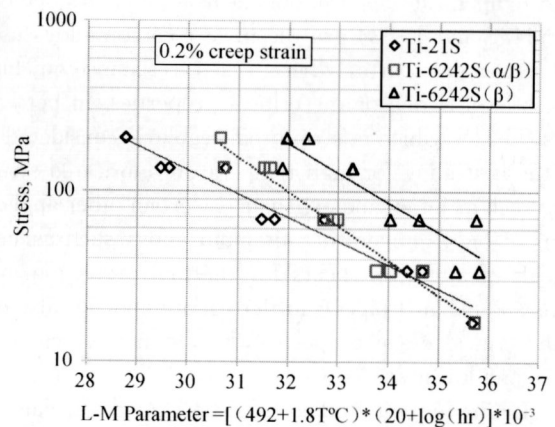
Temp (°C)	Alloy	Creep strain (%) at time			
		25 hr	35 hr	50 hr	100 hr
593	Ti-21S	0.43	0.50	0.56	0.68
	Ti-6242S ( $\alpha/\beta$ )	0.16	0.18	0.22	0.29
	Ti-6242S ( $\beta$ )	0.10	0.11	0.12	0.15
649	Ti-21S	0.55	0.67	0.84	stopped
	Ti-6242S ( $\alpha/\beta$ )	0.82	1.03	1.27	stopped
	Ti-6242S ( $\beta$ )	0.17	0.20	0.21	0.24



**Figure 2.** Typical creep curve showing creep strain (%) versus time (hr) for all three titanium alloys selected, at 593°C and 68.9MPa stress level

#### 3.2 Larson-Miller Parameter

L-M parameter at 0.2% creep strain for the present selection of alloys is calculated and presented in Figure 3. It is evident from Figure 3 that Ti-6242S in  $\beta$ -annealed condition has the best creep performance of the selected materials within the tested stress range. Ti-6242S ( $\alpha/\beta$ ) appears to have superior creep properties to Ti-21S; however, it is significant to note that the Larson-Miller parameter of Ti-21S seems to be quite similar to that of Ti-6242S ( $\alpha/\beta$ ) at stress levels 34.4MPa and 17.2MPa. This could mean Ti-21S could have creep resistance equivalent to Ti-6242S ( $\alpha/\beta$ ) at elevated temperatures and lower stresses.



**Figure 3.** Larson-Miller parameter (0.2% creep strain) calculated from creep test data of titanium alloys used in this study

#### 3.3 Steady-state Creep Rate

The slope of the creep curve in the secondary stage,  $d\epsilon/dt$  was measured and analyzed in this study. Creep rates for selected test conditions are presented in Table 4. As shown in Figure 2, 3 and Table 4, Ti-6242S ( $\beta$ ) displays the lowest creep rates at any test condition. Creep rate of Ti-21S at 34.5MPa is comparable to that of Ti-6242S ( $\alpha/\beta$ ).

**Table 4.** Calculated creep rate ( $\text{hr}^{-1}$ ) for the selected titanium alloys at  $593^\circ\text{C}$  at various stress levels

Material	Initial applied stress (MPa)			
	17.2	34.5	68.9	138
Ti-21S	$9.0 \times 10^{-4}$	$2.4 \times 10^{-3}$	$1.3 \times 10^{-2}$	$4.6 \times 10^{-1}$
Ti-6242S( $\alpha/\beta$ )	$4.0 \times 10^{-4}$	$1.4 \times 10^{-3}$	$4.6 \times 10^{-3}$	$4.1 \times 10^{-2}$
Ti-6242S( $\beta$ )	$3.0 \times 10^{-4}$	$6.0 \times 10^{-4}$	$5.0 \times 10^{-4}$	$3.2 \times 10^{-3}$

## 4. Discussion

### 4.1 Steady-state Creep

It is customary to describe creep by power law relationships between creep rate ( $\dot{\epsilon}$ ) and applied stress ( $\sigma$ )<sup>9)</sup>. Creep rate is a measure of steady-state rate of deformation where the dislocation structure has established a 'steady-state' in which generation and recovery of dislocations compensates each other so that there are no net structural changes. The stress exponent  $n = \Delta \log \dot{\epsilon} / \Delta \log \sigma$  of this creep rate is taken as one of the primary indicator of

the creep mechanism<sup>10)</sup>. Figure 4 shows all creep data for the materials used in this work, plotted as steady-state creep strain rate versus applied stress on double logarithmic scale. The slopes of these curves correspond to the steady-state stress exponent of these alloys under different test conditions.

The stress exponents obtained in the present work are reasonably consistent with values reported in earlier research<sup>3,11)</sup> performed on titanium alloys. Figure 4 also shows a transition in the stress exponent for the alloys Ti-21S and Ti-6242S ( $\beta$ ) to a value of  $\sim 1.0$ , as stress level is lowered which is in agreement with some of the previous work conducted<sup>12)</sup>. In accordance to the classical creep theory, a stress exponent of 1.0 may correspond to either diffusional creep or Harper-Dorn (H-D) creep mechanism.

As can be observed from Figure 4, the other stress exponents calculated are in the range of  $\sim 3$ -5, which are also consistent with research work performed earlier regarding rate controlling mechanism of creep in titanium alloys<sup>3,10,13)</sup>. These stress exponents correspond well to the fact that creep mechanism at low stress ( $\sigma \leq 150$  MPa) and temperatures ( $T < 750^\circ\text{C}$ ) is controlled by diffusion climb<sup>10)</sup>.

However assessment of appropriate rate controlling mechanism of deformation requires the information of activation energy for creep<sup>12)</sup>.

### 4.2 Activation Energy for Creep

For any given microstructural condition, the steady-state creep rate depends on stress and temperature and is usually described by a power-law equation of the type<sup>14)</sup>

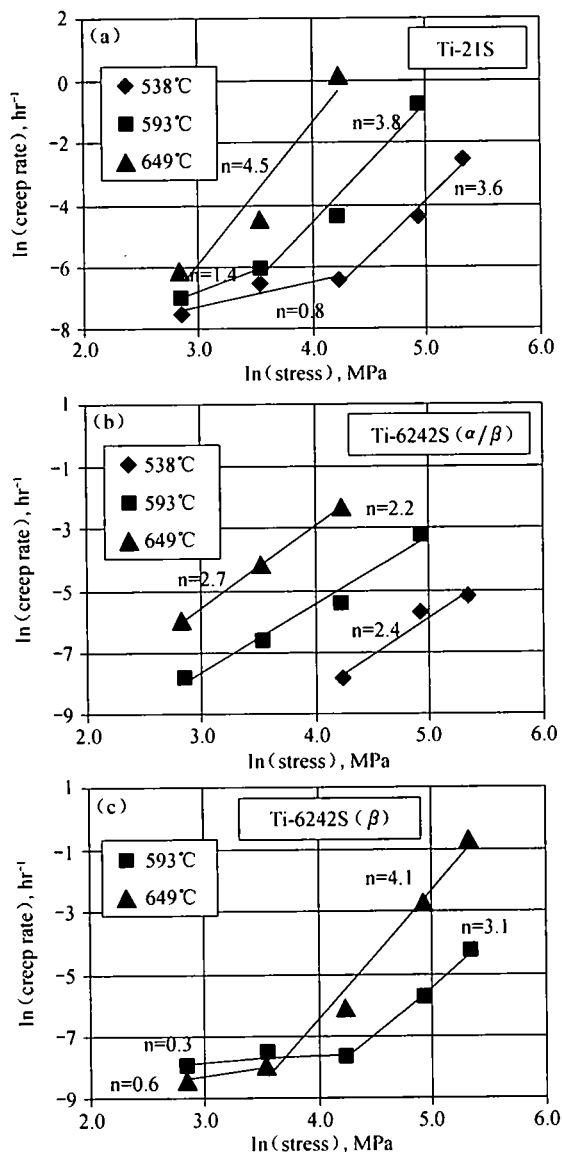
$$\dot{\epsilon}_s = A_0 \sigma^n \exp(-Q/RT) \quad (1)$$

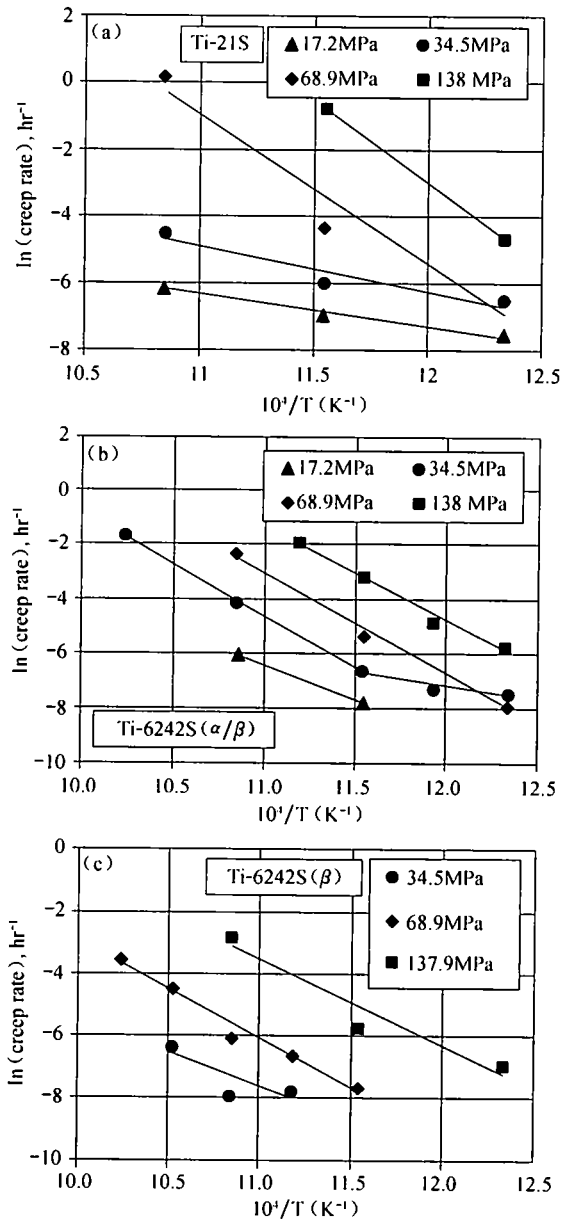
where  $\dot{\epsilon}_s$  is the steady-state creep rate,  $A_0$  is a constant depending on microstructure,  $\sigma$  is the applied stress,  $n$  is the stress exponent,  $Q$  is the activation energy for creep,  $R$  is the universal gas constant and  $T$  is the absolute temperature.

Figure 5 shows the Arrhenius plots as the variation of logarithm of steady-state creep rate with the reciprocal of the absolute temperature for all three materials used for this analysis. The calculated activation energies from the slopes of these curves are presented in Table 5. All values calculated for activation energies for the selected titanium alloys fall well within the region of self diffusion of titanium<sup>11)</sup>, except for the stress at 17.2 MPa. Variability of activation energy is due probably to lack of sufficient data. Nonetheless, the result suggests that dislocation climb can be one of the major mechanisms in all materials.

### 4.3 Microstructural Effects on Creep

There are several factors that control creep properties of Ti-6242<sup>15,16)</sup>. The microstructures of the materials used in this work consist of multiple phases and

**Figure 4.** Creep rate versus applied stress plotted on double logarithmic scale for the three titanium alloys selected for analysis



**Figure 5.** Arrhenius plots depicting creep rate versus reciprocal of absolute temperature. Activation energy is calculated from the slope of these curves

**Table 5.** Activation Energies (kJ/mol) at different stress levels calculated for the titanium alloys in the temperature range of 538°C to 704°C

Material	Initial applied stress (MPa)			
	17.2	34.5	68.9	138
Ti-21S	80	112	370	405
Ti-6242S (α/β)	208	316	308	290
Ti-6242S (β)	n/a	175	266	233

precipitates as shown in Figure 1. The microstructure of Ti-6242S (α/β) consists of primary α and transformed β grains that typically contain secondary α laths and retained β phase. Ti-6242S (β) consists of fully transformed α laths and retained β. Superior creep resistance of Ti-6242S (β) to Ti-6242S (α/β) is considered to be due to shorter dislocation slip length that is determined by lath spacing in coarse colonies. Cooling rate from β

region appeared to be important for creep resistance of Ti-6242S (β). Silicon improves creep resistance through solid solution hardening and the precipitation of silicides<sup>17)</sup>. The effect of ordered phase could be additional factor in Ti-6242S (β), since a slight ordering was detected when the material was annealed at 649°C<sup>16)</sup>.

Ti-21S consists primarily of fine α particles that precipitated upon duplex aging in the beta matrix. It is of interest that Ti-21S displays equivalent creep resistance to Ti-6242S (α/β) particularly at lower stress regime. This result could be due to finer α precipitates with lath morphology, which may reduce the mobility of dislocations in β phase, although further investigation was not conducted. Practically, strip producible β alloys may have a cost advantage over near α alloys if elevated temperature properties are equivalent.

### 5. Conclusions

Creep tests at high temperature-low stress regime were conducted. Creep strain of Ti-21S at higher temperature and low stress was noticed to be equivalent to Ti-6242S (α/β). Ti-6242S (β) however, has the better creep properties compared to the other materials used in this work. Calculation of stress exponent and activation energy values fall reasonably within the region of self-diffusion of titanium, as identified in some of the earlier research work conducted.

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### REFERENCES

- 1) Boyer RR, Mater. Sci. Eng. A, 1996, 213, pp. 103-114.
- 2) Froes FH, Suryanarayana C, J. Mat. Sci., 1992, 27, pp. 5113-5140.
- 3) Bania PJ, Hall JA, Titanium science and technology, Oberursel, Germany: Deutsche Gesellschaft fur Metallkunde; 1985, pp. 2371-2378.
- 4) J. C. Fanning and S. P. Fox, J. Mat. Sci., 2005, 14(6), pp. 703-708.
- 5) G. Malakondaiah and P. Rama Rao, Acta metall., 1981, 29, pp. 1263-1275.
- 6) Luetjering G, Albrecht J, Gysler A, Titanium '92 Science and Technology. Warrendale: TMS, 1993, 163-5.
- 7) Andres C, Gysler A, Luetjering G, Titanium '92 Science and Technology. Warrendale: TMS, 1993, 31-1.
- 8) Canon WR, Sherby OD. Metall. Trans. 1970; 1, pp. 1030
- 9) T. G. Langdon, Z. Metallkd., 1996, 2205, pp. 522-531
- 10) W. Blum, P. Eisenlohr, Mater. Sci. Eng. A, 2009, 510-511; pp. 7-13
- 11) F. Appel, U. Christoph, M. Oehring, Mater. Sci. Eng. A, 2002, 329-331; pp 780-787
- 12) R. W. Hayes, G. B. Viswanathan, M. J. Mills, Acta mater., 2002, 50, pp. 4953-4963
- 13) S. Gollapudi, V. Bhosle et al., Philosophical Magazine, 2008, 88 (9), pp. 1357-1367
- 14) M. Es-Souni, Materials Characterization, 2000, 45, pp. 153-164
- 15) Y. Kosaka, S. P. Fox, Ti-2007 Science and Technology, Vol. 1, pp. 255-258
- 16) P. Collins et al., unpublished work.
- 17) W. Cho, J. W. Jones, A. E. Allison and W. T. Dunlon, Proceedings of Sixth World Conference on Titanium, Edited by P. Lacombe et. al., les editions de physique, France, 1988, pp. 187-192